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AN ELEMENTARY TREATISE

ON

HEAT.

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AN ELEMENTARY TREATISE

ON

HEAT,

BY

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PREFACE.

THIS little work is intended as a text book for the M.B. Examination, the Special Examination in Applied Science, and the General Examination for the ordinary B.A. degree, in the University of Cambridge, the Matriculation and first B. Sc. Examinations of the University of London, the Examinations of the Science and Art Department, and for medical students generally. It is also hoped that it may be found useful as an introduction to the more elegant and complete treatises of Professors Maxwell, Balfour Stewart, Deschanel, and others by candidates for the Natural Sciences Tripos in Cambridge. A list of Articles which may be omitted by candidates for the General Examination will be found at the end of the Table of Contents.

A few Numerical Examples are worked out in the text; but those who are desirous of meeting with a large number of such would do well to consult the collection of examples on Heat by R. E. Day, Esq., M.A., Demonstrator of Experimental Physics in King's College, London. (Longmans, 1875.)

I have to acknowledge my indebtedness to the treatises on Heat by Professors Maxwell and Balfour Stewart, which I have had occasion several times to consult during the preparation of the present work. My thanks are also due to the Rev. A. Freeman, M.A., Fellow of St John's College, for some valuable suggestions.

In conclusion, I take this opportunity of expressing my sincere thanks to my friend Wm. M. Hicks, Esq., B.A., Scholar of St John's College, for his kindness in revising the proof-sheets, and for many important corrections and improvements.

WM. GARNETT.

ST JOHN'S COLLEGE, CAMBRIDGE,
March, 1876.

CONTENTS.

CHAPTER I.

On the Conservation of Energy and the connection between Dynamics and Heat.

PAGE
Work 1
Potential and kinetic energy 3
Unit of force 4
Conservation of energy 5
Conversion of kinetic energy into heat . . . . *ib.*

CHAPTER II.

On Temperature and its Measurement. The Mercurial Thermometer.

Cause of the sensations of heat and cold 8
Definition of Temperature 9
Comparison of temperatures 11
Construction of the Mercurial Thermometer 12
Graduation of the mercurial thermometer (Natural Standard) . . . 13
The Hypsometer 14
Scales of temperature . . . . *ib.*
Calibration of thermometer tubes 15
Conversion of temperatures from one scale to another 16
Rutherford's maximum and minimum thermometers 19
Advantages of the mercurial thermometer 20

CHAPTER III.

On Heat considered as a quantity. Specific heat. Calorimetry.

Distinction between a quality and a quantity 22
Heat is a quantity 23

PAGE
Unit of heat 24
Specific heat . . . . ib.
Capacity for heat 25
Method of mixture 26
Specific heat of copper . . . . ib.
Method of fusion 28
Calorimeter of Laplace and Lavoisier 29
Bunsen's Calorimeter . . . . ib.
Regnault's Calorimeters 30

CHAPTER IV.

Sources of Heat. The solid, liquid, and gaseous states. Expansion of solids and liquids, and practical applications of the same.

Sources of heat 33
Distinction between solids and fluids 35
Rigidity, elasticity and viscosity . . . . ib.
Distinction between liquids and gases 36
Coefficient of linear expansion . . . . ib.
Measurement of linear expansion 37
Coefficient of cubical expansion 38
Measurement of apparent expansion of liquids 39
Absolute expansion of mercury 40
Maximum density of water; Hope's experiment 41
Effect on climate of contraction of water by heat 42
Boilers, wheels, Armstrong and Fraser guns . . . . . . ib.
Graham's mercurial pendulum 44
Harrison's gridiron pendulum 45
Zinc-iron pendulum . . . . ib.
Chronometer balances . . . . ib.
Breguet's thermometer 47

CHAPTER V.

On the effects of Heat upon gases. The Gaseous laws. Cooling of gases by expansion. Specific heat of Air at constant pressure and at constant volume. Diffusion of gases.

Boyle's law 48
Expansion of air at constant pressure 49
The air thermometer 50

PAGE
Gay Lussac's law 51
Relation between pressure and temperature when the volume is constant *ib.*
Relation between pressure, volume, and temperature 53
Absolute zero of the air-thermometer 54
Differential thermometer 55
Heating of air by compression 56
Difference between the specific heats of air at constant pressure and at constant volume . . . . *ib.*
Air expanding into vacuum 57
Regnault's results . . . . *ib.*
Diffusion of gases 58
Explanation of diffusion in accordance with the molecular theory of gases . . . . *ib.*
Regnault's mercury pyrometer 59
Wedgwood's and Siemens' pyrometer 60

CHAPTER VI.

On the effects of Heat in producing changes of state in bodies. Latent heat. Regelation. Boiling and Evaporation. Dew-point. Spheroidal state. Thermo-electric pile.

Liquefaction 61
Latent heat of fusion . . . . *ib.*
Conversion of liquids into the gaseous state 62
Latent heat of evaporation . . . . *ib.*
The boiling-point 63
Determination of the latent heat of steam . . . . *ib.*
Singing of a kettle 64
Papin's digester 65
Measurement of heights by observations of the boiling-point of water . *ib.*
Melting-point of ice lowered by pressure 66
Regelation . . . . *ib.*
Freezing mixtures . . . . *ib.*
The Critical point 67
Boiling-point lowered by diminution of pressure 68
Evaporation 69
Amount of vapour in a given space, when saturated, depends only on the temperature . . . . *ib.*
Determination of the pressure of vapour at temperatures below the boiling-point 70

PAGE
The Dew-point . . . 70
Daniell's dew-point instrument . . . 71
Mason's dry and wet bulb thermometers . . . 72
Example on Hygrometry . . . *ib.*
Explanation in accordance with the molecular theory of gases . . . 73
Changes taking place in water when heated . . . 74
Spheroidal state . . . 75
Thermo-electricity . . . 76

CHAPTER VII.

On the transmission of Heat.

Conduction, convection, and radiation . . . 77
Thermal conductivity . . . 78
Comparison of thermal conductivities . . . 79
Law of conduction of heat . . . 81
Specific thermal conductivity . . . 82
Examples on thermal conductivity . . . *ib.*
Conduction in crystals . . . 84
Convection currents . . . *ib.*

CHAPTER VIII.

On radiant Energy.

Preliminary experiment . . . 86
Analysis of radiation . . . 87
Connection between light and other forms of radiant energy . . . 89
Laws of reflection . . . *ib.*
Absorption . . . 91
Laws of refraction . . . 92
Law of inverse squares . . . 93
Diathermancy of air . . . 94
Radiation and absorption by the surfaces of bodies . . . *ib.*
Prevost's theory of Exchanges . . . 95
Constitution of Flame . . . 99
Crooke's experiments on repulsion produced by radiation . . . 100
The Radiometer . . . 101

CHAPTER IX.

Meteorology.

PAGE
Land and sea breezes . . . 103
Trade winds . . . *ib.*
Counter trades . . . 104
The Gulf Stream . . . *ib.*
Formation of cloud . . . 105
Fog and mist . . . 106
Rain . . . 107
Hail and Snow . . . *ib.*
Dew . . . *ib.*
Hoar-frost . . . 108

CHAPTER X.

On the relations between Heat and Work.

Count Rumford's experiments . . . 109
Mayer's experiments . . . 110
Joule's experiments . . . *ib.*
Mechanical equivalent of heat . . . 111
Conversion of heat into work . . . 112
Specific heat of air at constant volume . . . *ib.*
Heat engines . . . 114
Efficiency of an engine . . . 115
Absolute Thermometric scale . . . *ib.*
Availability of heat . . . 116
Dissipation of energy . . . 117

Candidates for the General Examination may omit Arts. 7, 8, 46, 47, 65, 86, 92, 93, 95, 113, 126, 129, 130, 147—149, 153, 162—166, 169, and 186—194.

CHAPTER I.

ON THE CONSERVATION OF ENERGY AND THE CONNECTION BETWEEN MOTION AND HEAT.

1. *Force is said to do work when it moves its point of application.*

The work done by a force which remains uniform in magnitude and direction, is measured by the product of the number of units of force, and the number of units of length through which its point of application is moved *in the direction of the force,* that is, through which the force *works.*

If the weight of 1 lb. be the unit of force, and 1 foot the unit of length, the work done by a force equal to the weight of 1 lb. in working through one foot is the unit of work, and is called a *foot-pound.*

For example, if a weight of 10 lbs. be allowed to fall from a height of 6 feet to the ground, since the earth exerts an attractive force upon it *in the direction of motion* equal to the weight of 10 lbs., the work done upon the body by gravity is 60 foot-pounds.

2. Work is said to be done *against* a force, when the point of application is made to move (by some agent) in the direction *opposite* to that in which the force acts, and is measured by the product of the number expressing the force and that expressing the distance moved over by its point of

application in the direction opposite to that in which the force acts.

Thus, if the 10 lb. weight above mentioned be raised from the ground to its original position at a height of 6 feet, 60 foot-pounds of work are done *against* gravity.

3. If the point of application of the force do not move in the same straight line in which the force acts, we must determine the whole distance through which it has moved parallel to this straight line, and if this be given the work done by, or against, the force is independent of the path along which this point moves.

Thus the work done in lifting 1 cwt. of bricks to the top of a scaffolding 40 feet in height will be the same, viz. 4480 foot-pounds, whether the bricks be raised in a basket over a pully along a vertical straight line through 40 feet, or whether they be carried in a hod up an inclined ladder, or wheeled in a barrow up planks at a small inclination to the horizon, although in this last case the whole distance through which they are moved is *very much* greater than 40 feet. We see then, that in order to find the work done against gravity, we have simply to multiply the weight of the body in pounds by the vertical height through which it is raised in feet, and the product is the required number of foot-pounds of work, and a similar process will give us the work done by gravity on a descending body, the weight of the body and the *difference of level* between its initial and final positions being all that concerns us, the form of the *path* described having no influence on the result.

4. If a weight of 10 lbs. be suspended at a height of 6 ft. from the ground by a string passing over a *smooth* pully it will be able, in descending, to lift a weight less than 10 lbs., but differing from it by a quantity as small as we please, and attached to the other end of the string, through the same height; and we may therefore say that in virtue of its *position* relative to the earth, it is capable of doing 60 foot-pounds of work upon another body, or to speak more correctly, the system composed of the 10 lb. weight *and* the earth, is capable of doing 60 foot-pounds of work

in virtue of the relative positions of these bodies. Similarly if a spring be compressed it is capable of doing work (in virtue of its compression) when allowed to resume its natural form.

Again, if we succeed in catching a cricket-ball in one hand, we are conscious of a pressure exerted by the ball on the hand, and we also observe that the ball compels the hand to move backwards over a certain distance in the direction in which the ball is moving, that is, in the direction in which it presses the hand. Hence the ball does an amount of work on the hand, which, if the pressure exerted by it were uniform, would be measured by the product of this pressure, and the distance through which the hand moves in the direction of the pressure. The ball is therefore capable of doing work *in virtue of its motion.* If the ball were to fall on the top of a spring it would bend the spring by doing work upon it, and would thus put the spring in a position to do work on being allowed to regain its original form. (It may be shewn that the amount of work the ball can do is proportional to the product of its mass and the square of its velocity.)

5. Hence we see that a system of bodies may be capable of doing work in virtue of its *configuration,* that is the relative position of its parts, or, of *its motion.* The whole amount of work which a system is capable of doing is called its *energy.* That portion of its energy which is due to its motion is called its *kinetic* energy, while that portion of the energy which is due to its configuration, is called *potential* energy.

6. Potential energy and Kinetic energy are mutually convertible. Thus if a weight of 10 lbs. be held at a height of 6 ft. above the ground, it may be said to possess 60 foot-pounds of potential energy in virtue of its position relative to the earth. If it be allowed to fall *freely* from this height, at the instant it reaches the ground its potential energy is zero, but it has a considerable velocity, and the kinetic energy it possesses in virtue of this motion is exactly equivalent to 60 foot-pounds. If the velocity were now reversed (as by striking against a perfectly elastic horizontal plane)

this kinetic energy would be at first the same as before, but the body would now continue to rise, losing velocity and therefore kinetic energy as it went, until it would come to rest at a height of 6 ft. from the ground where its kinetic energy would be zero, since it would be at rest, but its potential energy would be 60 foot-pounds. Of course if it remained unsupported it would immediately begin to descend again, and the same cycle of events would be repeated, so that we should have the potential energy originally possessed by the ball, alternately converted into kinetic energy, and this reconverted into potential energy. This actually takes place in the case of the motion of a clock pendulum, or any *vibrating* body, the energy of which is *potential* when at the extremity, and *kinetic* when in the middle, of its swing. The energy of a bent spring is potential energy, while that of a cannon-ball after its discharge is kinetic energy.

7. It should be observed that the units of force and of work we have adopted, viz. the weight of a pound, and the foot-pound, both belong to a class of variable units called *gravitation units*, for *a pound* is properly a definite *quantity of matter*, and its *weight* depends upon the locality in which it is placed, as well as its height above the sea-level, since the intensity of gravity varies both with the latitude and the distance from the earth's centre. On this account these units are not well adapted for general use throughout the world, and other units, called absolute units, which do not depend on the attraction of the earth, have been employed to supersede them.

The British Absolute unit of force is that force which acting on a pound of matter for a second, generates in it a velocity of one foot per second, and the British Absolute unit of work is the work done by this force in working through one foot.

This unit of force is rather less than the weight of half an ounce in the latitude of London.

8. Newton in commenting on the third law of motion makes a statement which may be translated as follows :—

"*If the action of an agent be measured by the rate at which it works, and the reactions of the resistances, whether arising from friction, cohesion, or weight by the rate at which work is done against them, and if amongst these reactions we include the rate at which kinetic energy is being generated in the system, action and reaction in all combinations of machines are equal and opposite.*"

This statement is equivalent to asserting that when an agent does work on a system, the whole of the work done is equivalent to the work done against gravitation, cohesion, friction (and other forces) together with the kinetic energy generated in the system. Now we have seen that when work is done against gravity, an equivalent amount of potential energy is conferred on the body which is raised, and the same is true when work is done against any forces which, like gravity, are independent of the time and the motion of the system. Hence if a system be acted on by forces of this nature only, Newton's statement is equivalent to the assertion that the work done on the system by any agent is equivalent to the change in the sum of the potential and kinetic energies produced by it. This is a case of the great Principle of the Conservation of Energy. In particular, we see that *if no external agent affect the system the sum of its potential and kinetic energies will remain constant.*

9. If work be done against friction, or force of a like nature, no potential energy is conferred on the moving system, for friction always acts so as to prevent motion, and can therefore have no tendency to bring a body back into its original position, as gravity tends to do when a weight is raised.

The work done against friction, therefore, appears at first sight to be lost, and for a long while this was believed to be the case. It has its equivalent, however, in a mode of motion which we have not yet considered.

10. If a brass button be rubbed vigorously on a board and then applied to the skin, we become conscious that the button is *hot.* The physical agent which produces this sensation is called *heat.* Now the work done upon the button by the person rubbing it is not in this case converted into

energy of position, as the button may be finally brought to rest at the point from which it started, nor is any portion of it finally converted into the energy of motion of the button as a whole, since it is at last brought to rest. It remains then for us to discover what has become of the work done on the button.

11. If a resined bow be rubbed against the string of a violin, both friction and adhesion tend to retard the motion, and work has to be done against these forces by the hand of the violinist. After the passage of the bow the instrument emits a musical note, and on examination it is found that the string is in a state of *vibration*, a state which it also communicates to the wood of the violin, whence most of the sound is emitted. In this case the work done by the hand of the violinist is partly transformed into the energy of the vibrating string and sound-board, and thence into the energy of sound-waves in air.

Again, if a number of elastic wires have each one end stuck into a board, like bristles in a brush, and the hand be made to pass over their tops, the work done by the hand will produce vibrations in the wires which will be in part communicated to the board. Now the surface of any body which is not perfectly smooth, a condition fulfilled by no known object, consists of a series of small projections, and the passage of a rough surface over these causes them to vibrate, in the same manner as vibrations are set up by the passage of the hand over the wire brush, or of the bow over the violin-string, though, of course, on a very much smaller scale. Now it is the passage of these projections on each surface, over one another, that is the cause of friction, and the work done against friction is consumed in setting up vibrations in these small portions of matter, these vibrations being continually communicated to the other material particles in contact with them, so that vibrations are set up in every particle of which the button or other body is composed. (All natural surfaces possess projections of this nature; the art of polishing consists in making them as small as possible. A surface is highly polished when they are small compared with the length of a wave of light, or the 50,000th *of an inch.)* It is this state of vibration which when communicated to our nerves produces the *sensation of heat,* and the whole of the work done against friction is converted into the energy of vibration of the particles of which the bodies which rub against each other are composed. (The part played by local electric currents in this production of heat has not been clearly made out.)

12. We can now place the principle of conservation of energy on a broader basis than before, comprehending within it those cases in which work is done against friction and similar forces, and may enunciate it thus:—

When an agent does work on any material system, the whole of the work done is equivalent to the change of the sum of the potential energy and kinetic energy of the system, including in the latter the whole energy of vibration set up in the material particles of which the system is composed.

We thus see that the work done against friction and supposed by Newton to be lost, has its equivalent in molecular vibrations, constituting heat, generated in the system.

If the system do work against external forces, its whole energy is diminished by the equivalent of the work so done.

13. In the case of the vibrating violin-string, the vibrations are communicated by the sound-board of the instrument, and, in small part, by the string itself, to the surrounding air, through which they are propagated to distant objects, and their energy is lost by the violin. In a similar way the vibrations which we have said constitute heat in bodies, are slowly imparted to a medium which fills all space, viz. the ether, and are propagated by it to distant bodies in the form of radiant energy, as described in Chapter VIII., and energy is thus lost by the body in which it originally existed as heat. This form of radiant energy is sometimes, but improperly, termed radiant heat.

Heat is also lost by a body on account of its communicating its molecular vibrations to the material particles of other bodies in contact with it. This mode of communicating heat is called *conduction,* and will be discussed in Chapter VII.

CHAPTER II.

ON TEMPERATURE AND ITS MEASUREMENT. THE MERCURIAL THERMOMETER.

14. IF we place a poker in a fire, and after some time remove it, it feels *hot*. The physical cause of this sensation is called *heat*. A piece of iron which has been exposed to the air will generally feel *cold*.

If we hold for some time in the right hand a piece of iron which feels hot, and then grasp the right hand with the left, the left hand will experience a sensation of heat, or the right hand will feel hot to the left, and at the same time the left hand will feel cold to the right. The same will be true if we hold for some time in the right hand any other body which feels hot. The fact that the right hand feels hot to the left after holding the hot iron, while it may have felt neither hot nor cold before, proves that the hand has received heat from the iron. We therefore infer that when a body feels hot to the hand, it imparts heat to the hand while touching it. It then follows that, because the right hand feels hot to the left hand, heat must pass from the right hand to the left. But the left hand feels cold to the right hand, and associating this sensation with what we have just proved, viz. that heat passes from the right hand to the left, we infer that a body feels cold to the hand when heat passes from the hand to the body. We may arrive at the same conclusion by holding in the right hand a piece of very cold iron, after which the right hand will feel cold to the left, and the left hand warm to the right. Now, the fact *that* the left hand feels warm to the right, shews that heat passes from it to the right hand, and we infer that this also is the reason why the right hand feels cold to the left. Also the fact that the right hand has been made to feel cold to the left by its contact with the iron, shews that heat must have left the hand and entered the iron, which accounts for the latter feeling cold to the hand.

15. We thus see that a body feels hot to the hand when heat passes from the body to the hand, and cold when it passes in the opposite direction. The sensations of heat and cold are therefore essentially *relative.* This may be further illustrated thus:—

Place the right hand in a mixture of ice and salt and the left hand in hot water, then place both in cold water; the cold water will feel warm to the right hand and cold to the left, shewing that the sensation of heat or cold depends on the condition of the hand relative to the hot or cold body, and is not an absolute property of the body itself. The water in a bath sometimes feels warm to the hands and cold to the feet.

16. *The quality of a body, in virtue of which it seems hot or cold, is called its temperature.* If a body feel hot to the hand, it is said to be at a higher temperature, and if it feel cold, at a lower temperature, than the hand. Now we have seen that a body feels hot or cold according as heat passes from it to the hand, or from the hand to it. The direction of the flow of heat then, in this case, determines whether the body or the hand is at the higher temperature; and applying the same criterion in all cases, to determine whether of two bodies is the hotter, we may define temperature thus:—

DEF. *The temperature of a body is its thermal condition with reference to its power of communicating heat to, or of receiving heat from, other bodies; the body* A *being said to have a higher temperature than B if heat pass from A to B when they are placed in contact.*

17. It follows from the definition just given that if, when two bodies are placed in contact, no heat flows in

either direction, the bodies are at the same temperature. They are then said to be in *thermal equilibrium* with each other. Now *it is found experimentally* that if two bodies *A* and *C* are each in thermal equilibrium with a third body *B*, then if *A* and *C* be placed in contact no heat will flow in either direction, or they will be in thermal equilibrium with each other. Hence we infer that, *bodies which are in thermal equilibrium with the same body, are in thermal equilibrium with each other;* and our definition is consistent with itself when it directs us to assign to them all the same temperature, viz. that of the body with which they are all in thermal equilibrium.

18. If we touch in succession several bodies all of which feel hot, some will feel hotter than others; and similarly, if we touch several bodies all of which feel cold, we shall experience sensations of different degrees of coldness. Now if all the bodies are formed of the same material, and in the same mechanical condition, we are justified in assuming that, of two hot bodies, that is of the higher temperature which feels the hotter, and similarly for two cold bodies. But if the bodies be of different materials we are no longer justified in making this assumption, and for this reason; viz. the power of a hot body to produce the sensation of heat does not depend *entirely* on its *thermal* condition with reference to its power of communicating heat to other bodies (that is, on its temperature), but depends also on the rate at which it can transmit heat through its substance, and this is different for different materials. Thus a piece of iron and a hollow piece of wood may both feel hot, and the iron feel much hotter than the wood; yet if the iron be placed in the hollow of the wood for some time, it may then feel hotter than before, thus showing that heat has passed from the wood to the iron, and that the iron was therefore originally at a temperature *lower* than that of the wood. Again, if a piece of iron and a piece of wood be in contact for a long while in a hot place, the iron will feel much the hotter though it is in thermal equilibrium with the wood, and therefore at the same temperature as the latter. This is due to the difference in the conducting powers for heat of iron and wood, and *will be discussed* in a subsequent chapter.

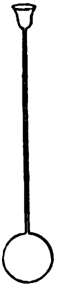
19. In order, then, to determine whether of two bodies *A* and *B* is the hotter, we ought to place them in contact, and determine in which direction the heat passes; but as this is frequently a very difficult, or impossible, operation, recourse must be had to some more convenient method. This is generally accomplished by taking a third body *C*, very small compared with *A* or *B*, and called a thermometer. This is placed in contact with *A* till it is in thermal equilibrium with it, and therefore at the same temperature; and subsequently in contact with *B*, till it is again in thermal equilibrium, and therefore at the temperature of *B*; and it is ascertained whether the temperature of *C* is higher when in equilibrium with *A* or with *B* by observation of some property of the body *C*, which changes with its temperature, as, for example, its volume.

20. All bodies, with very few exceptions, expand when heated, and contract again on cooling, so that, other things being the same, their volume increases as the temperature rises, and returns to its original value when the body regains its original temperature. Suppose it possible to measure accurately the volume of a given small quantity of some substance, as, for instance, mercury. Then if the mercury be placed in contact with each of any number of bodies in succession, till it is in thermal equilibrium with it, and its volume be measured in each case, we can arrange the series of bodies in order of temperature.

21. Suppose *K*, *L*, and *M* to be three bodies of which *K* is the coldest and *M* the hottest. Then, although we can arrange the bodies in order of temperature by means of the small quantity of mercury, or other substance, whose volume we measure, yet we are not at present in a position to tell whether the difference between the temperatures of *K* and *L* is greater, equal to, or less than, the difference between the temperatures of *L* and *M*; in fact we have as yet no graduated scale of temperature. Now, if our thermometer consist of a given mass of mercury, we may, if we please, assume that equal increments of temperature are such as produce equal increments in the volume of the mercury, and it will then follow that the difference between the tempera-

tures of two bodies is proportional to the difference in the volume of a given mass of mercury when in thermal equilibrium with the first and second body respectively. We are thus enabled to form an arbitrary *scale of temperature* which will depend upon the properties of the particular substance (in this case mercury) which forms our thermometer. As, however, the mercurial thermometer is used much more extensively than any other, before alluding to other scales of temperature we shall describe the construction and mode of graduation of the ordinary mercurial thermometer.

FIG. 1.



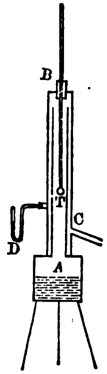
22. To construct a mercurial thermometer a glass tube of very fine bore is taken, and a small bulb is blown at one end, while a cup is formed at the other extremity as shewn in Fig. 1. In this cup is placed a small quantity of mercury, and the bulb is then heated over a flame. The air in the bulb expands when heated, and a considerable portion of it escapes by bubbling up through the mercury in the cup. The bulb is then allowed to cool, when the pressure of the air within it diminishes (as explained in Chapter V.); the pressure of the external air then drives some of the mercury in the cup down the tube and into the bulb. If it be desired to take great care in the construction of the thermometer, this process is repeated until the bulb and a portion of the tube is filled with mercury when at the ordinary temperature, but in general a more expeditious process is adopted. A small portion of mercury having entered the bulb as described above, the latter is heated until the mercury boils, when the heavy mercury vapour drives out the lighter air at the top of the tube, and, when the whole of the air has been expelled, the bulb and tube are filled with mercury vapour (except the space occupied by the liquid mercury remaining in the bulb). The instrument is then allowed to cool, and as the mercury vapour condenses, the mercury in the cup is forced into the tube by the pressure of the external air, and, except for a very small quantity of air which may have been left behind, the bulb and tube are completely filled with liquid mercury. The instrument is then heated to a temperature somewhat

higher than the highest for which it is intended to be subsequently used, when the mercury expands so as to completely fill the tube, and drive out any residue of air which may have been left above it. The top of the tube is then sealed with the blowpipe while the mercury remains hot. The instrument should be kept for some months after the bulb has been blown before it is graduated, because glass after being highly heated does not acquire its permanent volume for some time, and this is the reason why in the filling of the best thermometers, to be used for moderate temperatures only, the mercury is not boiled, but the air is driven from the bulb by heating it slightly many times in succession.

23. It remains to graduate the thermometer. Now it is found that under ordinary atmospheric pressure pure ice always melts at the same temperature, which is called the freezing point, and also that the temperature of the steam above the surface of boiling water depends only on the barometric pressure to which it is subjected. A pressure of 29·898 inches of mercury at freezing temperature is generally taken as the standard pressure, and the temperature of the steam above the surface of water boiling under this pressure is always the same, and is called the boiling point. If the height of the barometer differ from this standard height, in graduating the thermometer a small correction has to be made in consequence.

In order to graduate the instrument it is first placed in melting ice, and a mark made on the tube at the height at which the surface of the mercury stands. This mark corresponds to the freezing point, and should always be determined before the boiling point, because after being heated to the latter temperature, the glass does not contract to its proper volume for some time, and, if the freezing point were determined immediately after the boiling point, the mark would after some time be found to be too far down the tube. In determining the freezing point the thermometer should be immersed so far in the ice that the surface of the mercury is only just visible above it, in order that the *whole* of the mercury may have the temperature of the ice.

FIG. 2.



24. In order to determine the boiling point, the instrument shewn in Fig. 2 and called a hypsometer is employed. This instrument consists of a vessel *A*, containing water, the upper portion of which is a tube open at the top. Over this tube is placed the wider tube *BC*, which is closed at *B* by a perforated cork through which the stem of the thermometer *T* passes. *C* is a small tube for the exit of the steam, sloping downwards in order to allow the ready escape of condensed water. *D* is a small bent tube containing water, which is sometimes attached to the instrument to indicate if the pressure of the steam within exceed that of the external air. When the water in *A* is made to boil, the thermometer soon becomes surrounded by an atmosphere of steam, which is itself surrounded by a steam-jacket, on account of the steam having to pass down between the tubes before escaping at *C*. The thermometer is pushed through the cork at *B* till the surface of the mercury is only just visible above it, in order that the whole of the mercury may be exposed to the same temperature. The stem is then scratched at the level of the surface of the mercury (the height of the barometer being observed at the same time, in order to make any necessary correction for the pressure not being the standard pressure of 29·898 inches of mercury). The mark so placed upon the tube is called the *boiling point.*

25. It remains now to subdivide the stem of the thermometer between the freezing and boiling points into degrees, and to mark off degrees above the higher and below the lower of these temperatures. There are three different modes of doing this in general use in different parts of Europe, in other words, there are three distinct *scales of temperature.* In Fahrenheit's scale, which is chiefly adopted in England, the freezing point is marked 32° and the boiling point 212°. The tube between these points is then divided into 180 equal portions, and divisions equal to these marked off above 212° and below 32°. In the scale of Celsius, better known as the Centigrade scale, the freezing

point is marked 0°, and the boiling point 100°, the tube between these points being divided into 100 equal parts and equal divisions marked off along the rest of the tube. This scale of temperature is now almost universally adopted by scientific men. The third scale of temperature, viz. that of Réaumur, is in very general use in ordinary life on the Continent. In it, as in the centigrade scale, the freezing point is marked 0°, but the boiling point is marked 80°. This scale, like that of Fahrenheit, has little to recommend it in preference to the centigrade, except its general use in some localities.

26. We shall now suppose that we are graduating a centigrade thermometer, and that the freezing and boiling points have been marked upon its stem as described above. If the thermometer is not required for very accurate measurements the remainder of the work is very simple. The length of tube between the freezing and boiling points is divided into 100 equal parts, and these are marked off upon the tube, or on a box-wood or metal scale attached to it, by means of a dividing engine or otherwise, equal divisions being then carried on throughout the remainder of the tube. Each division thus marked is called a degree, and those degrees below freezing point, which is the zero of the scale, are marked negative.

27. Now it is obvious that if there be any inequalities in the bore of the thermometer tube in different parts, equal lengths of the tube will not always correspond to equal increments in the volume of the mercury relative to that of the glass. The above mode of graduation is therefore not sufficiently exact for accurate instruments. In order to remove this cause of error, a small pellet of mercury, of a convenient length, is detached from the rest of the column, and by inclining and gently tapping the tube, is made to occupy different positions within it. The length of the pellet in each position is carefully measured, and, since its volume is constant, it follows that, if the length of a degree at any part of the tube is made proportional to the length of the pellet when occupying this position, each degree will correspond to the same increment of the apparent

volume of the mercury in the glass. This process is called calibrating the tube. The division of the tube is then conducted on this principle, and it is obvious that some amount of care and calculation is required in effecting it. A small pellet of almost any desired length can generally be removed from the rest of the column by tapping it so as to remove a long pellet, warming it, re-uniting the pellet to the column, cooling it and again tapping the tube. A pellet will then break off at the same point of the tube at which the last united to the column, and the column being shorter in this case, the pellet will be shortened by an equal amount. By carefully repeating this process we can remove a very short pellet.

It should be noticed that the expansion of the mercury with which we have been dealing, is not its actual increase of volume, but its *apparent* expansion when contained in a glass vessel, and is the difference between the actual increase of volume of the mercury and that of the interior of the part of the glass vessel containing it. This is generally called the *apparent* expansion of mercury in glass.

28. It is very important to be able to convert temperatures expressed in one of the three above-mentioned scales, into the corresponding temperatures of either of the other scales.

Suppose F°, C°, and R° to represent the scale-reading of Fahrenheit's, the Centigrade, and Réaumur's thermometer respectively, corresponding to any, the same, given temperature. Now the freezing point on Fahrenheit's scale is marked 32°. Hence $F-32$ is the number of degrees Fahrenheit of the given temperature, *above the freezing point*, while C and R express the same in degrees of the Centigrade and Réaumur's scale respectively. But the excess of the temperature of the boiling point above that of the freezing point is 180°, 100°, and 80° on the three scales respectively, and the excess of any other temperature above that of the freezing point expressed in degrees of these scales, will therefore be proportional to these numbers. Therefore $F-32 : C : R :: 180 : 100 : 80.$

We have therefore the following rules:—

(I) Since $C : R :: 100 : 80 :: 5 : 4$, in order to convert temperatures on the centigrade scale into corresponding temperatures on Réaumur's scale, multiply by 4 and divide by 5. To perform the inverse process, i.e. to convert degrees Réaumur into degrees centigrade, multiply by 5 and divide by 4.

(II.) Since $F-32 : C :: 180 : 100 :: 9 : 5$, in order to convert temperatures expressed in Fahrenheit's scale into the corresponding centigrade temperatures, subtract 32 from the reading of Fahrenheit's scale, and multiply the result by 5 and divide by 9. To perform the inverse process, multiply the reading of the centigrade scale by 9, divide by 5 and add 32.

For example

$$212^\circ\text{F.} = \frac{5}{9}(212-32)^\circ\text{C.} = \frac{5}{9}180^\circ\,\text{C.} = 100^\circ\,\text{C.}$$

$$55^\circ\,\text{C.} = \left(\frac{9}{5}55+32\right)^\circ\text{F.} = (99+32)^\circ\,\text{F.} = 131^\circ\,\text{F.}$$

(III) Since $F-32 : R :: 180 : 80 :: 9 : 4$, in order to convert readings of Fahrenheit's scale into the corresponding readings on Réaumur's scale, and vice versâ, proceed as in rule (II) only replacing the 5 by 4. Thus

$$212^\circ\,\text{F.} = \frac{4}{9}(212-32)^\circ\,\text{R.} = \frac{4}{9}180^\circ\,\text{R.} = 80^\circ\text{R.}$$

$$44^\circ\,\text{R.} = \left(\frac{9}{4}44+32\right)^\circ\text{F.} =. (99+32)^\circ\,\text{F.} = 131^\circ\,\text{F.}$$

It may be useful to remark that certain temperatures on Fahrenheit's scale, in addition to the freezing and boiling points, have received particular names; for example, 55° F. is marked *temperate*, 76° F. *summer-heat*, and 98° F. *blood-heat*.

The student unaccustomed to such calculations will find it useful to work out the following examples.

Express in degrees Centigrade the following temperatures:

1.	56° R.	Ans.	70° C.
2.	77° F.	„	25° C.
3.	59° F.	„	15° C.
4.	329° F.	„	165° C.
5.	56° F.	„	13·3̇° C.
6.	98° F.	„	36·6̇° C.
7.	108° F.	„	42·2̇° C.
8.	10° F.	„	−12·2̇° C.

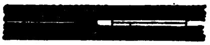
Express in degrees Fahrenheit:

1.	56° R.	Ans.	158° F.
2.	40° C.	„	104° F.
3.	60° C.	„	140° F.
4.	−40° C.	„	−40° F.
5.	−10° C.	„	14° F.
6.	309° C.	„	588·2° F.

29. Coloured sulphuric acid is sometimes used instead of mercury for filling thermometers, it having the advantage of expanding more for a given change of temperature, and thus allowing a wider tube to be employed, so that the surface is more distinctly visible. Coloured alcohol is also employed for very low temperatures, since mercury solidifies at about −40°C. Alcohol is also employed in *minimum* thermometers, which will be presently described. When liquids other than mercury are employed, the thermometers are generally graduated by comparing them with a standard mercurial thermometer at various temperatures, and subdividing the tube between the graduations so obtained, and in the case of the alcohol thermometer, marking off on the portion of the tube which corresponds to temperatures below those measurable by the mercurial thermometer divisions equal to the lowest of those which can be directly determined by the latter instrument.

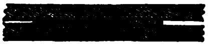
30. The *maximum* thermometer is an instrument used for registering the highest temperature to which it has been exposed since it was last adjusted. It consists of an ordinary mercurial thermometer, in the tube of which is placed a small steel index, or needle, represented by *a b* in fig. 3, which shews a section of the tube in the neighbourhood of the index. The thermometer is kept horizontal, and when the mercury expands its convex surface *c* pushes the index before it. When the mercury contracts it leaves the needle behind as shewn in the figure. The end *a* of the needle will therefore always indicate the highest temperature to which the instrument has been exposed since it was last adjusted. To adjust the instrument the index is brought back into contact with the mercury by means of a magnet.

FIG. 3.



The minimum thermometer is employed to register the lowest temperature to which it has been exposed. It consists of an alcohol thermometer, placed horizontally, and containing in its tube a small index of glass, or enamel, as shewn in fig. 4. Since the alcohol wets the glass its surface will be concave as shewn at *c* instead of convex as in the case of mercury. When the alcohol contracts the surface *c* pushes the index back with it, but when it expands, the index being entirely wetted by the spirit, it is left behind. The end *a* of the index will then shew the lowest temperature to which it has been exposed. The instrument is set by inclining it until the index slides down to the surface *c* of the spirit.

FIG. 4.



These thermometers are known as Rutherford's maximum and minimum thermometers.

31. If fluids other than mercury be employed for thermometers, and the scales be constructed so that the readings of the instruments correspond with those of the mercurial thermometer at two particular temperatures, and the tubes between these points be divided into the same number of equal portions as that of the mercurial thermometer, it will be found that at intermediate temperatures

the thermometers will not agree, but the reading will in general be different for each different fluid. This shews that the scale of temperature in which the degrees correspond to equal increments in the apparent volume of mercury contained in a glass vessel is an entirely arbitrary scale, and different from that which would be obtained if any other fluid were employed. At first sight there appears no reason why mercury should be used for the determination of a scale of temperature in preference to other substances. It has however the following advantages over other liquids.

(1) It remains liquid through a very wide range of temperature, viz. from about −40°C. to about 351°C.

(2) It quickly takes up the temperature of the substance in which it is immersed without much changing the temperature of that substance on account of its great power of transmitting heat (i.e. its conducting power), and secondly on account of the small quantity of heat required to raise a given quantity of it through a given range of temperature (i.e. its low specific heat).

(3) Although in general the scales of temperature deduced from the expansion of different substances are different, yet there is a class of fluids, viz. the permanent gases, including air, which, by the law of their expansion under constant pressure, all indicate almost precisely the same scale of temperature. Now since this scale is indicated by several bodies independently, there is very much more reason why it should be adopted than that indicated by any single substance only. In addition to this the scale of the air thermometer very nearly coincides with the *Absolute* thermometric scale, deduced from certain thermodynamic considerations, and briefly described in Chapter X. These facts give to the indications of the air thermometer a peculiar value which places its scale far above that of any other substance (except the other permanent gases, all of whose scales correspond with it)*. Now it happens that the scale of temperature in which the degrees correspond to

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* This scale of the air thermometer possesses also another peculiarity, viz. that the *same amount of heat* is required to raise in temperature a given mass *of air at constant* pressure through each degree of the scale.

equal apparent increments of the volume of mercury contained in glass agrees almost exactly with that scale in which the degrees correspond to equal increments of volume of dry air or other permanent gas at constant pressure. This alone is a sufficient reason why mercury should be employed in the construction and graduation of thermometers by the method above described. When mercurial thermometers of extreme accuracy are required for scientific observations their indications are sometimes compared with those of the air thermometer, and a table of corrections made, so that temperatures can be determined by them as nearly as possible in accordance with the scale of the air thermometer. The last mentioned instrument will be described in Chapter V.

Throughout the remainder of this work all temperatures will be expressed in degrees of the mercurial thermometer, except when otherwise stated.

CHAPTER III.

ON HEAT CONSIDERED AS A QUANTITY. SPECIFIC HEAT. CALORIMETRY.

32. IN the preceding Chapter we have discussed the modes of measuring temperature, and we have throughout spoken of *degrees*, and not *quantities*, of temperature; because hitherto we have seen in temperature only a *quality* which affects bodies, and not a *quantity* which can be dealt with by the ordinary laws of arithmetic, for in so far as we have at present discussed temperature we can assign no meaning whatever to the operation of adding together two temperatures, or of multiplying a temperature by any number. If we mix together two equal quantities of a substance at the same temperature, the temperature of the mixture is not the sum of the temperatures, but is *equal to that of either*, and if their temperatures be originally unequal, the temperature of the mixture is intermediate between that of its components. Temperature is in this respect analogous to many other qualities possessed by bodies, as, for example, hardness. We may say that a body *A* is harder than a second body *B* if *A* will scratch *B*, but cannot be scratched by it, and we may then select a number of bodies, each of uniform hardness, and number them so as to form an arbitrary scale. The number attached to each substance will then represent its degree of hardness. We may, for example, take the hardnesses of the following substances as the standards of reference for our arbitrary scale, calling that of Talc 1, Rock-salt 2, Calcareous spar 3, Fluor spar 4, Apatite 5, Felspar 6, Rock-crystal 7, Topaz 8, Corundum 9, Diamond 10. Now, suppose a piece of glass will scratch *Apatite* but is scratched by Felspar, we say then that its

degree of hardness lies between 5 and 6. Again, suppose a penknife will scratch Felspar but not Rock-crystal, then we say that its hardness lies between 6 and 7. We cannot however assign any meaning to the operation of adding together the hardness of the glass and knife, and so can never have to determine whether the result would be a hardness greater than that of the diamond or of any other substance, nor can we compare the interval between the hardnesses of any two substances in our scale with the corresponding interval for any other pair.

33. The case is however different with the agent which is the cause of increase of temperature in bodies, namely, heat itself. If we take a pound of water at 1°C. it will require a certain definite amount of heat to raise its temperature to 2°C. under given conditions, and a second pound of water will require an equal amount of heat to produce the same change of temperature under the same circumstances. Consequently the two pounds require *twice* the amount of heat required by the one pound to produce the same change of temperature, so we see that heat must be of the nature of a physical *quantity* which is subject to the ordinary operations of arithmetic (i.e. addition, subtraction, &c.), and we are therefore justified in speaking of *amounts*, and not of *degrees*, of heat.

34. Since, then, heat is a physical *quantity*, it is of importance to compare the amounts of heat required to produce given changes in definite portions of matter. If a pound of water at 0°C. be mixed with a pound of water at 2°C. the mixture will be found to have a temperature of 1°C., so that the heat which leaves 1lb. of water when its temperature falls from 2°C. to 1°C. is just capable of raising the temperature of 1lb of water from 0°C. to 1°C. We learn, therefore, from this experiment, that the *same amount of heat* is required to raise the temperature of 1lb. of water from 1°C. to 2°C. as from 0°C. to 1°C., and therefore the amount of heat required to raise 1lb. of water from 0°C. to 2°C. is *twice* that required to raise it from 0°C. to 1°C. Similarly if we mix together 1lb. of water at 0°C. and 1lb. at 4°C. the temperature of the mixture will be found to be 2°C., from

which we infer that the amount of heat required to raise 1lb. of water from 2°C. to 4°C. is equal to that required to raise it from 0°C. to 2°C.; whence it follows that the amount of heat required to raise 1lb. of water from 0°C. to 4°C. is four times that required to raise it from 0°C. to 1°C. If we proceed in this way with water at higher temperatures we shall find that the temperature of the mixture is rather greater than the mean of its components. Thus if we mix 1lb. of water at 0°C. with 1lb. at 80°C. the temperature of the mixture will be about 40·14°C.; from which we infer that the amount of heat required to raise a pound of water 1°C. when at a high temperature is rather greater than that required to raise it 1°C. at a low temperature. If, however, the temperature of the water be not high, we may say that the amount of heat required to raise the temperature of a pound of water through $N°C.$ is N times the amount required to raise the same quantity of water from 0°C. to 1°C.

35. The expression of any physical quantity consists of two factors, one of which is the unit in terms of which it is measured, and *of the same nature as the quantity considered*, while the other is a pure number shewing how many times the quantity contains this unit, and is called the *measure* of the quantity.

Hence in order to express the magnitude of any physical quantity we must fix upon an invariable unit of its own kind. Examples of such units have been given in Chapter I.

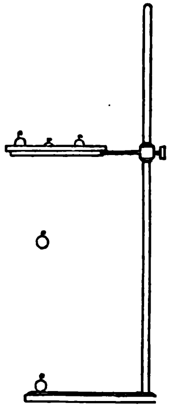
DEF. *The unit of heat is the amount of heat required to raise the temperature of 1lb. of water from 0° C. to 1° C.* This quantity of heat is sometimes called a *calorie.*

36. DEF. The *specific heat of a substance at any temperature is the ratio of the amount of heat required to raise the temperature of any mass of the substance 1° C. from the given temperature, to the amount of heat required to raise the temperature of an equal mass of water from 0° C. to 1° C.*

From this definition it will be seen that the specific heat of a substance at any temperature is equal to the number of *units of heat* required to raise the temperature of one pound of the substance 1°C. from that temperature.

The number of units of heat required to raise the temperature of a body 1° C. is called its CAPACITY FOR HEAT.

FIG. 5.



37. The fact that equal volumes of different metals have different capacities for heat may be shewn experimentally by heating a number of equal spherical balls of different metals, say copper, iron, tin, zinc, lead, and bismuth, to 100° C., and then laying them on a thin cake of wax. The copper ball will quickly melt its way through the wax and be followed almost immediately by the iron ball, the copper preceding the iron because, though its specific heat is only ·095 while that of iron is ·113 per unit of mass, yet the density of the copper is greater than that of the iron, and the copper also more readily allows of the passage of heat from its interior. Shortly after the iron, the zinc ball, whose specific heat is ·0955, will fall, while the lead, whose specific heat is ·03, and the tin, whose specific heat is ·056, will perhaps be unable to melt their way through, and the bismuth ball, whose specific heat is nearly the same as that of lead but whose density is much less, will only make a comparatively shallow impression in the wax.

38. Referring to the properties of water mentioned in Art. 34 it will be seen that the specific heat of water is nearly unity, if its temperature be not much above 0° C., but at higher temperatures its specific heat is rather greater than unity. It continues to increase with the temperature.

39. The operation of measuring quantities of heat is called *Calorimetry;* and an instrument adapted to this purpose is called a *Calorimeter.*

The process of determining the specific heat of a substance, consists in finding the amount of heat required to produce a given change of temperature in a known mass of the substance, and is therefore an operation in Calorimetry. We shall now describe some of the methods usually adopted for measuring quantities of heat.

THE METHOD OF MIXTURE.

40. An illustration of this method has already been given, when we shewed how to prove experimentally, that the amount of heat required to raise the temperature of a pound of water from 1° C. to 2° C., was equal to the amount required to raise an equal mass of water from 0° C. to 1° C. It consists essentially in mixing together known quantities of two substances at different temperatures, the specific heat of one of which is known, and determining the temperature of the mixture. In most cases water is taken as the substance whose specific heat is known, the other substance may be a liquid or a solid, but it must not act chemically on the water. The method will be best understood by taking another example.

Suppose we wish to determine the specific heat of copper. We weigh out a convenient quantity, say 500 grains, of copper and suspend it, by a fine thread, in the steam above the surface of water boiling in a vessel almost closed, but allowing sufficient means of egress for the steam to prevent its pressure becoming sensibly greater than that of the atmosphere. If the barometer stand at 30 inches, the copper will after some time have acquired a temperature of about 100° C. While the copper is being heated we weigh out carefully a quantity of distilled water, say 1000 grains. This is placed in a vessel whose capacity for heat is small, and after the vessel and water have acquired the same temperature, this temperature is very carefully observed. Suppose it to be 12° C. The copper is now removed from its hot bath and plunged as quickly as possible into the cold water, where it is moved up and down by means of its suspension thread, until thermal equilibrium between it and the water is attained. (It is important that this process should require as small a time as possible, and to this end the copper should not have a very small surface. A coil of copper wire answers the purpose very well.) The temperature *of the water* is then again carefully observed; and the time elapsing between the immersion of the copper and the observation of this temperature should also be noticed. Suppose the temperature to be 15·7° C. The ratio of the mass of the copper to that of the water in the calorimeter should, if possible, be so arranged that the temperature of the air in the room is intermediate between the first and last observed temperatures in the calorimeter, and somewhat nearer to the latter than the former. This can be insured if the specific heat of copper be known approximately. The loss of heat by radiation and conduction from the instrument will then be exceedingly small, but in extremely accurate measurements this must be determined and allowed for. This condition would be fulfilled in the case we are considering, if the temperature of the air in the room were between 14° C. and 15° C., or even somewhat higher. Now if we neglect the capacity for heat of the vessel containing the water, we have sufficient data to obtain a rough approximation to the specific heat of copper. The number of degrees of temperature lost by the 500 grains of copper is $100 - 15{\cdot}7$ or $84{\cdot}3$, and the heat leaving the copper serves to heat 1000 grains of water 3·7° C., and would therefore heat 500 grains of water 7·4° C. The mean specific heat of copper between the temperatures 15·7° C. and 100° C. is therefore $\frac{7{\cdot}4}{84{\cdot}3} = {\cdot}0877\ldots$

41. The result just obtained is, obviously, too small, because we have neglected the heat taken up by the vessel containing the water, when the temperature of the latter is raised. In order to determine this approximately, we may refill the vessel with cold water, and after allowing it to stand for a considerable time, observe its temperature. Suppose it again to be 12°C. Now empty the vessel as thoroughly as possible, and place in it 1000 grains of water at say 15° C., this temperature being accurately observed before pouring the water into the vessel. After this has stood for some time, say rather less than the time above referred to, let the temperature be again observed. Suppose it to be 14·77° C. Now the amount of water at 12° C., which must be mixed with 1000 grains at 15° C. to reduce the whole to 14·77° C., is about 83 grains. The presence of the vessel then is equivalent to increasing the amount of water from 1000 to

1083 grains. Making allowance then for this, we see from the results just obtained, that the amount of heat required to raise the temperature of 500 grains of copper 84·3 degrees, will raise 1083 grains of water 3·7 degrees; and would therefore raise the temperature of 500 grains of water

$$\left(\frac{3{\cdot}7 \times 1083}{500}\right)^{\circ}\text{C}.$$

The mean specific heat of copper between 15·7° C. and 100°C. is therefore

$$\frac{3{\cdot}7 \times 1083}{500 \times 84{\cdot}3} = {\cdot}095\ldots$$

This result is very nearly correct.

As another example of this method the student may take the following:—

1000 *grains of mercury at* 100° *C. are mixed with* 1000 *grains of water at* 15° *C. contained in a vessel, which, on account of its capacity for heat, is equivalent to an increase of* 100 *grains in the quantity of water within it. The resulting temperature is* 17·5° *C. Find the specific heat of mercury.*
Ans. ·033.

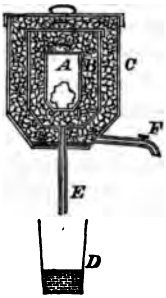
THE METHOD OF FUSION.

42. If we mix together 1 lb. of water at 79° C. with 1 lb. of water at 0° C., we obtain 2 lbs. of water at 39·5° C., very nearly. If however we mix together 1 lb. of water at 79°C. with 1 lb. of ice at 0°C., we obtain 2 lbs. of water at 0°C. From this we see that in order to melt 1 lb. of ice at 0° C. without changing its temperature, we require as much heat as would raise 1 lb. of water 79° C., in other words, we require 79 units of heat. This number, 79, is called the *latent heat* of water, and will be more fully discussed in a subsequent chapter; it is introduced here because this property of ice is made the basis of the construction of several instruments for measuring quantities of heat, known as *ice calorimeters,* two of which we shall now describe. We must so far trespass upon the matter of subsequent chapters as to state, that while pure ice is melting under ordinary pressure, the tem-

perature of the ice and water remains accurately at 0° C. till the whole of the ice is melted.

43. The calorimeter of Laplace and Lavoisier consists of three vessels. The inner vessel *A* is formed of thin metal and contains the heated body. This is placed in the interior of a larger vessel, *B*, which forms the calorimeter proper, the space between them being filled with broken ice, and this again is placed within a still larger vessel, also packed with broken ice to prevent absorption of heat from surrounding bodies by the calorimeter proper. A small pipe passes through the outer vessel from the bottom of the calorimeter proper, and serves to convey the water from *B* into a vessel placed for its reception. Now since *B* is surrounded by ice at 0° C. the ice within it can only melt by taking up the heat which passes from the body in *A*, and since 1 lb. of ice requires 79 units of heat to melt it, we can determine the amount of heat which leaves the body in *A*, by weighing the water which falls into the vessel *D*. The body in *A* is of course finally reduced to the temperature of the ice in *B*, that is, to 0° C. The pipe *F* simply conveys away the waste water from the ice jacket.

FIG. 6.

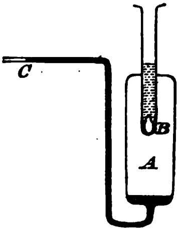


44. Suppose the body in *A* to be 500 grains of copper originally at 100° C., and suppose that the flow of water from *B* ceases when 60 grains have escaped. We know that the temperature of the copper is then 0° C. Now the heat required to convert 60 grains of ice at 0° C. into water at the same temperature, would raise 79 × 60 grains, or 4740 grains, of water 1° C. Hence the heat lost by 500 grains of copper in cooling from 100° C. to 0° C. would raise 4740 grains of water 1° C. The mean specific heat of copper between 0° C. and 100° C. is therefore $\frac{4740}{500 \times 100} = \cdot 0948$.

45. The action of Bunsen's Calorimeter depends on the fact that ice contracts considerably when melting, and the

water continues to diminish in volume as its temperature increases between 0° C. and 4° C. It consists of a vessel *A* containing water, into the upper part of which a test-tube *B* is sealed, and the whole vessel is thus closed except for the fine tube *C*, which is graduated, and, together with the lower part of *A*, filled with mercury. The instrument is first placed in a freezing mixture of ice and salt until a considerable portion of the water in *A* is frozen; it is then removed and placed in pure melting ice or snow, which just covers the vessel *A*. Cold water is then placed in the test-tube, and when it has attained a temperature of 0° C., as indicated by the surface of the mercury in the tube *C* becoming stationary, the position of the surface in *C* is observed. The body whose capacity for heat is to be measured, having been heated to 100° C. in steam, is now placed in the test-tube *B*. This heats the water in *B* which in its turn communicates the heat to that in *A*, thus melting some of the ice and causing the surface of the mercury in *C* to move. The decrease in the volume of the contents of *A* is measured by the movement of the mercury in *C*, and thus the amount of ice melted in *A* can be found. Also no heat can have entered *A* except from the test-tube since it is surrounded by melting snow, and nearly all the heat lost by the body in *B* will enter *A*, for the bulk of the water in *B* being at 0° C., since water contracts in volume as its temperature rises from 0° C. to 4° C., that warmed by the hot body is *heavier than the rest*, and does not rise to the surface. The amount of ice melted in *A* therefore enables us to measure the heat lost by the body in *B* in cooling from 100° C. to 0° C. Several measurements can be made with the instrument without again placing it in the freezing mixture.

FIG. 7.



46. Other forms of calorimeters have been employed for the measurement of the specific heats of gases and liquids. The most perfect are those devised by Regnault. In order to determine the specific heat of a gas at constant pressure, he makes a known quantity pass from a holder through a

metal "worm" which is immersed in heated oil. In this it acquires the temperature of the oil, and thence it passes through a complicated metal vessel immersed in the water of the calorimeter. Here it acquires the same temperature as the water, while the temperature of the latter is gradually raised. The temperature of the water being observed at the commencement and close of the experiment, after making proper correction for the capacity of the apparatus, we can find the number of units of heat given up by the gas to the calorimeter. Now all the gas has been heated to the temperature of the oil, while the temperature to which it was cooled in the calorimeter was variable. Since however the temperature of the calorimeter will increase almost uniformly, the result is the same as if the whole of the gas had been cooled to the temperature, which is the arithmetical mean of the initial and final temperatures of the calorimeter. Knowing the mass of the gas, we have now sufficient data for the calculation of its specific heat.

47. The principal peculiarity of Regnault's calorimeter for liquids, is the artifice for preventing loss of heat by the liquid, on account of exposure in passing from the bath in which it is heated to the calorimeter. This consists in forcing the liquid by means of atmospheric pressure, from the vessel in which it is heated, and which is immersed in a hot bath, through a tube into a vessel immersed in the water of the calorimeter, the latter instrument being prevented from receiving heat directly from the hot bath, to which it is placed very close, by means of a screen.

48. We may observe that in the case of substances which, like water, are known in the solid, liquid and gaseous states, the specific heat of the liquid is greater than that of either the solid or the gas.

49. The methods described in this chapter only enable us to measure quantities of heat which pass from one body to another, the receiving body being the water, or ice, of the calorimeter; they will not enable us to form any idea of the whole amount of heat contained in a body, because we cannot get the whole of the heat to pass out of any

body into another. Consequently if we speak of the whole amount of heat contained in a body, we use a phrase to which we can assign no meaning, and, as the student will learn after studying the effect of heat upon gases, the amount of heat required by a body to cause it to pass from one given temperature to another, frequently varies considerably with the conditions as to pressure, &c. to which it is subject, and is not a definite quantity unless these conditions be specified, though its variations are usually extremely small in such cases of liquids and solids as we have generally to deal with. It was on account of these considerations, that in first introducing heat as a measurable quantity, we did not say that the whole amount of heat contained in two pounds of water at 1° C., was equal to twice the amount contained in one pound at the same temperature, but spoke of the amount of heat required to raise different quantities of water from 1° C. to 2° C. *under given conditions.* Since, in the cases of water and most other liquids and solids, the amount of heat required to produce a given change of temperature varies very slightly with ordinary variations of external circumstances, the words in italics are generally omitted, but this statement will not apply to gases.

CHAPTER IV.

SOURCES OF HEAT. THE SOLID, LIQUID, AND GASEOUS STATES. EXPANSION OF SOLIDS AND LIQUIDS, AND PRACTICAL APPLICATIONS OF THE SAME.

50. We have seen that one effect of heat upon bodies is, in general, to increase their temperature, and in Chapter II. we have seen how to measure temperature in degrees of an arbitrary scale, while in the last Chapter we discussed the measurement of quantities of heat. We must now briefly enumerate the most frequent sources of heat with which we are acquainted, and then consider the effects of heat upon bodies.

51. The principal sources of heat are,

(I) *Radiant energy.*

The sun's radiation is by far the most important source of heat in which we are practically interested. When radiation falls upon bodies capable of absorbing it, it is generally converted into heat in the bodies, and raises their temperature. The other effects of radiation will be noticed subsequently.

(II) *Chemical action.*

Under this head we include combustion, which is the principal source of heat which man has at his command for domestic, manufacturing, and other purposes. Animal heat is due to this cause.

(III) *Mechanical sources,* including friction, impact, the change of form and volume of imperfectly elastic bodies however produced, &c.

In all these cases we have work done by a force, and only in part converted into potential energy due to the strain produced. Most of the remainder of the work done is converted into heat.

(IV) *Electric currents,* including those currents of very short duration, such as lightning flashes, which are more generally known as electric discharges.

(V) *The internal heat of the earth.*

This last differs from the preceding sources, inasmuch as the heat exists in the earth *as heat* before it comes under our notice, and is therefore not a source from which heat is *produced,* but simply a store from which it is *derived.* Volcanic heat has been applied to commercial purposes in the preparation of borax.

52. If we trace back any supply of heat as far as possible we find that, if we neglect such unimportant sources as meteors, we always arrive either at the internal heat of the earth, the earth's motion of rotation converted into heat by the intervention of the tides and machinery driven by them, or the radiation from the great centre of our system, the sun. Take for example the heat generated in a wire, through which an electric current due to a zinc-carbon battery is passing. This heat is derived from the energy of the current, which is itself derived from the combination of the zinc with the exciting liquid. Now this energy is due to the attraction of the zinc for certain components of the liquid, and for the energy of this attraction the zinc is indebted to the heat which separated it in the reducing furnace from its combination with oxygen, &c. in the ôre. This heat is due to the combustion of the coal, and therefore to the attraction which the coal possesses for oxygen, and for this attraction the coal is indebted to the energy of the solar radiation, *which, acting through* the machinery of a vegetable organ-

ism, separated the carbon, &c. from combination with oxygen at the time when the trees grew from which our coal is produced.

EFFECTS OF HEAT UPON MATTER.

53. Bodies may be divided into two classes, *solids* and *fluids.*

DEF. *A solid is a body which requires a finite force to produce a finite change in its form with or without change of volume.*

DEF. *A perfect fluid is a body whose form can be changed to any extent, provided its volume remain constant, by the application of a force, however small, if we allow it sufficient time.*

One solid is said to be more *rigid* than another, when, other things being the same, it requires a greater force to produce in it the same change of form. A solid would be *perfectly rigid* if no finite force, however great, could produce any change whatever in its form or volume. We know of no body perfectly rigid or perfectly fluid.

As illustrations we may refer to a piece of hard steel, which requires a very great force to produce a permanent impression upon it; while its weight is sufficient to make any quantity of water acquire the form of the vessel into which it is poured.

A body is said to be *elastic* when it tends to return to its original form or volume after the force of constraint has been removed. Fluids are elastic for changes of volume only, and have no tendency to assume any particular shape. (The spheroidal form assumed by drops of liquid is due to the combined action of gravity and a tension of the *surface* of the liquid known as *surface tension.* Capillary action is due to the same cause.)

There are many substances which occupy a kind of intermediate position between solids and liquids, as, for example, many vegetable gums, &c., and are called *viscous.*

54. Fluids are divided into two classes, viz. *liquids* and *gases*.

DEF. *A liquid is a fluid, a finite portion of which cannot be made to occupy more than a certain definite volume, however the pressure to which it is exposed may be diminished.*

DEF. *A gas is a fluid, any finite portion of which may be made to occupy any space, however great, by sufficiently diminishing the pressure to which it is exposed.*

For example, if a cup of olive oil, or strong sulphuric acid, be placed under the receiver of an air-pump the liquid will not sensibly change its volume, however perfect a vacuum may be formed around it; while if a cubic inch of air at ordinary pressure be allowed to enter an exhausted receiver of *any* capacity, the air will expand and completely fill the receiver, exerting an uniform pressure all over its surface, as may be shewn by the same fall being produced in columns of mercury in manometer tubes communicating with the receiver at different points.

55. We have seen that the effect of the entrance of heat into bodies is in general to increase their temperature, and this is *usually* accompanied by increase of volume, if the pressure to which they are subject be not increased so as to prevent it. Water between the temperatures of 0° C. and 4° C., and baked clay, are, however, notable exceptions to this rule, since they contract on increase of temperature.

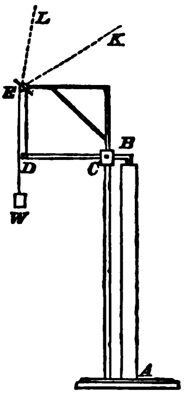
Amongst solids the metals as a general rule expand most for a given increase of temperature.

DEF. *The ratio of the increase in length of a bar of any substance, due to an increase in its temperature of* 1° *C., to the original length of the bar, is called the coefficient of linear expansion of the substance.*

Thus if the length of a bar of copper is one foot at 0°C. and 1·0017 feet at 100°C., its mean coefficient of expansion between 0°C. and 100°C. is ·000017; for if the expansion were uniform between 0°C. and 100°C. its length at 1°C. would be 1·000017 feet, and the ratio of the expansion to the *original length* would then be ·000017.

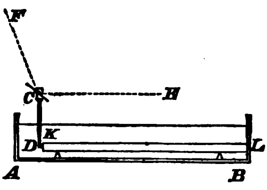
56. The expansion of a bar of lead by a slight increase of temperature may be shewn by fixing the end *A* of the bar *AB* (fig. 8), while upon the end *B* the extremity of the short arm of the lever *BCD* is allowed to rest, the other end of the lever being attached to a string which passes round an exceedingly small pully at *E*, and sustains a weight *W*. To the pully at *E* a small mirror, upon which a beam of light, *KE*, is made to fall, is attached, the reflected ray, *EL*, from which falls upon a scale. If a warm hand be applied to the bar *AB* it will expand, depressing *D*, and causing the pully and mirror to turn through a small angle which is rendered quite appreciable by the motion of the spot of light formed on the scale by the rays reflected from the mirror.

FIG. 8.



57. The linear expansion of bars may be conveniently measured by means of the apparatus shewn in fig. 9. *AB* is a bath of oil or water which can be heated to any required temperature, and the temperature observed by means of a thermometer. *CD* is a small bar which can turn about a centre at *C*, and carries a blunt knife-edge at *D* resting against the end *K* of the bar *KL*, whose expansion is to be observed. The arm *CD* carries a small mirror near *C*, and the distance between the centre of motion *C* and the knife-edge at *D* is accurately known. The end *L* of the bar *KL* rests against a fixed obstacle, as, for instance, the end of the vessel, and the centre *C* and end of the vessel *B* should be so supported that the distance between *C* and *L* is invariable. The adjustment should be so made that during the experiment the mean position of the line *CD* is as nearly as possible vertical. A ray of light is allowed to fall on the mirror in the direction *EC*, which remains constant, and is

FIG. 9.



reflected along *CF*, forming a spot of light on a scale conveniently situated. When the bar *KL* is heated it expands, and the end *K* pushes *D* before it, since *L* is fixed. This causes the arm *CD*, and with it the mirror, to turn about *C*, the reflected ray *CF* consequently being deflected through twice the angle through which *CD* turns. This angle is indicated by the deflection of the spot of light on the scale, and hence the angle through which *CD* turns, and therefore the distance through which *D* moves, or the linear expansion of *LK*, can be at once determined.

This method is similar to that of Lavoisier, who employed a telescope attached to the arm *CD* instead of the mirror, and through it observed a fixed scale. The mirror has the advantage of being much lighter than the telescope, and therefore more easily mounted, while it deflects the ray through twice the angle through which it turns. It will not however admit of such exact measurements being made as will the telescope.

58. DEF. *The coefficient of cubical expansion of a substance at any temperature is the ratio of the increment of any volume of the substance produced by an increase in its temperature of* 1° *C. to the original volume.*

Most substances, except crystals, expand equally in all directions when heated. Imagine a cubical block, the length of whose edge is 1 foot: its volume will then be 1 cubic foot. Now suppose that on raising its temperature 1°C. the length of its edge becomes $1+\alpha$ feet, so that α is its coefficient of linear expansion. Then its volume is $1+3\alpha+3\alpha^2+\alpha^3$ cubic feet, and the increment of its volume is $3\alpha+3\alpha^2+\alpha^3$ cubic feet. The ratio of this to the original volume, viz. one cubic foot, is $3\alpha+3\alpha^2+\alpha^3$, which expression is therefore the coefficient of cubical expansion. Now α is, in general, very small; hence α^2 and (*a fortiori*) α^3 may be neglected in comparison with α. We have then for the coefficient of cubical expansion 3α, or *the coefficient of cubical expansion is three times the coefficient of linear expansion* for the same substance.

In the case of copper α is about ·000017. Hence 3α is about ·000051, $3a^2$ about ·000000000867 and a^3 about ·0000000000000004913. It is obvious that both $3a^2$ and a^3 may be neglected without producing any sensible error in the result, each being far less than the limits of experimental error in the determination of a.

59. If a liquid be heated in a glass vessel, both the glass and the liquid expand. The *apparent* expansion of the liquid in the vessel is due to the difference between the expansion of the liquid, and that of the interior of the vessel. There are two methods in general use for the measurement of this expansion. The first consists in filling with the liquid the bulb and part of the stem of a thermometer tube, the capacity of the bulb and different parts of the length of the stem at some particular temperature being accurately known. By observing the height of the liquid in the stem at the first temperature, the volume of liquid at that temperature is known. The liquid is then heated, and the height again observed, whence the *apparent* increment of volume can be found.

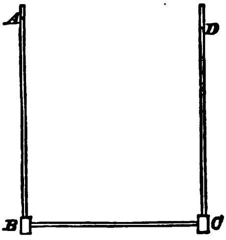
60. In the second method a specific gravity bottle is usually employed. This consists of a glass bottle, into which a stopper, having a small hole drilled through it, is accurately ground. The bottle having been weighed is completely filled with the liquid whose expansion is to be measured, and whose temperature is known. The stopper is then inserted, when the excess of liquid escapes through the perforation, and is carefully wiped away. The bottle and contents are then weighed, and deducting the weight of the bottle from the result of this weighing, we have the weight of the contents. The temperature of the bottle and liquid is then raised, and as the liquid expands it escapes through the stopper, and is wiped off. On again weighing the bottle we determine the amount of liquid which has escaped, and the ratio of this to the amount remaining is the ratio of the whole increment in volume between the two temperatures to the original volume.

61. Now if we can determine the absolute expansion of *some particular liquid*, as well as its apparent expansion in a

glass vessel due to the same change of temperature, the difference between the two will give us the expansion of the vessel, and then, knowing the apparent expansions of other liquids in the same vessel, we shall only have to add to these quantities the expansion of the vessel, which we have determined once for all, in order to obtain the absolute expansion of all these liquids. The determination of the absolute expansion of some particular liquid is therefore of very great importance, and mercury is the liquid which has been employed for the purpose.

The method by which this has been effected may be briefly described as follows:—

FIG. 10.



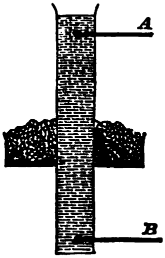
Two tubes *AB* and *CD* are placed as nearly vertical as possible, the ends *B* and *C* being connected by a fine tube which is at right angles to the vertical tubes and therefore in a horizontal position. The tubes are then nearly filled with mercury, and *AB* is surrounded with a cylinder containing oil, not shewn in the figure, and which can be heated to the desired temperature. The tube *DC* is surrounded by a cylinder containing melting ice. The heights of the cylinders are so adjusted that the mercury in each tube is just visible above the top of the cylinder surrounding it. When the mercury in each tube has acquired the temperature of the surrounding bath, the heights of the columns *AB* and *CD* are carefully measured. Then since the mercury in the horizontal tube *BC* is in equilibrium, the pressure at *B* due to the column *AB* is equal to that at *C* due to the column *CD*. Hence the densities of the mercury in these two columns are inversely as their heights, and therefore the volume of a given quantity of mercury at the temperature of either column will be proportional to the height of the column. The ratio of the difference of the heights of the two columns to that of the shorter will therefore represent the total absolute expansion of an unit of volume of mercury between the temperature of the ice, i.e. 0°C., and of the oil. The coefficient of expansion for mercury at 0°C. is thus found to be about ·000179.

A knowledge of this coefficient is necessary to enable us to reduce readings of the barometer to the corresponding readings when the mercury in the instrument is at 0°C.

62. Having thus obtained sufficient data for determining the absolute expansion of different liquids, we may determine the cubical expansion of a solid by weighing it in a liquid at different temperatures, the coefficient of absolute expansion of the liquid being known; and this process is not unfrequently adopted.

63. All bodies, with very few exceptions, expand as their temperature rises, provided they retain the same state of aggregation, i.e. remain solid, liquid or gaseous throughout the change. Exceptions to this law are however met with in baked clay, stretched caoutchouc, which when heated contracts in the direction of its tension, and water between 0°C. and 4°C., of which the last mentioned is by far the most important. If a quantity of water at 0°C. be heated, it contracts in volume as its temperature rises till it reaches a temperature of nearly 4° C., when its density is a maximum; if heated beyond this temperature it expands, and at a temperature between 7° C. and 8°C. its volume is equal to that at 0°C. It then goes on expanding, its coefficient of expansion per degree of the mercurial thermometer increasing slightly as the temperature rises. This peculiarity of water may be exhibited by filling a tall cylindrical jar, *AB*, with water, say at 12°C., small thermometers being inserted into the liquid at *A* and *B*. The middle of the jar is surrounded by a freezing mixture. As the water in the neighbourhood of the freezing mixture is cooled, its density increases, and it descends, causing the thermometer at *B* to indicate a rapid fall of temperature, while that at *A* is very slightly affected. This goes on till the thermometer at *B* reaches a temperature of about 4°C., when it will cease to fall, but the thermometer at *A* will now indicate a fall in temperature, and will continue to do so down to 0° C., when ice will begin to be formed at the surface.

FIG. 11.



64. We may remark here that water on freezing expands by nearly nine per cent. of its volume, so that the ice formed floats on the surface of the water. This behaviour of water is of immense importance in the economy of nature, for when a quantity of water, as, for instance, a lake, cools at the surface, the cold water descends, warmer water from below taking its place; and this goes on till the whole lake has attained a temperature of 4° C., after which the cold water remains at the surface until a layer of ice is formed there, which prevents the rapid cooling of the remainder of the water on account of the extreme slowness with which it transmits heat. We consequently find that in deep lakes the water below a certain depth is at 4° C., however cold that at the surface may be. Were water to continue to contract till it froze, we should have the whole of the water in lakes reduced to 0° C. during a continuance of cold weather, and if it also contracted on cooling, we should get an immense quantity of ice accumulated at the bottom of lakes, till the whole lake became frozen; for during the summer, the water warmed by the sun's rays would float at the top, and the ice below would only be affected by the small quantity of heat transmitted through this water, and thus the ice would increase from year to year, till the whole lake became frozen in the winter, and melted in the summer only to a very small depth.

65. The expansion of metals when heated, and their subsequent contraction on cooling, have been turned to practical account in several of the arts. Thus boiler-plates are rivetted with red-hot rivets, which on cooling contract, and draw the plates together so tightly as to form a joint impervious to high-pressure steam. Again, tyres for ordinary carriage-wheels, as well as the steel tyres for the wheels of locomotives and railway carriages, are fitted on when red-hot, and on cooling grip them with very great force. The same property of iron is utilised in the manufacture of the Armstrong and the Fraser gun. In these guns, the breech is surrounded by a number of iron cylinders, made by winding bars into helices, and welding each turn to the next so as to form a cylinder in which the fibre of the iron is arranged in a helix about the axis of the gun. The first cylinder is turned so as to fit easily over the breech of the gun when the latter

is cold but itself red-hot. It is then heated and slipped into its position, after which the gun is immersed in cold water. On cooling, the cylinder tends to contract, and exerts great pressure on the breech. The next cylinder is turned so as to fit over the first in a similar way, and so on, Armstrong guns sometimes having 5 or 6 cylinders placed one over the other. Each cylinder, except the outside one, is then subject to an enormous pressure, on account of the tendency of the cylinder surrounding it to contract upon it, while in its turn it exerts pressure on the cylinder within it. Hence when the powder explodes, the pressure of the gases produced has to balance the contractile forces of all the cylinders, before it can exert any force effective in producing a strain on the breech of the gun. Guns thus constructed will consequently bear the explosion of very heavy charges without bursting; a pressure of about 70 tons weight per square inch being sometimes exerted within them.

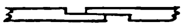
We may also mention, that the walls of a museum in Paris which had bulged outwards, were drawn together by passing iron bars through them across the building, heating the latter, and, when expanded, screwing nuts upon their projecting ends. On cooling, the bars drew the walls together, and the process was repeated till they assumed their proper positions.

66. An idea of the force which iron exerts if prevented from contracting when cooled from a high temperature to ordinary temperatures, may be gathered from the following rough calculation.

Suppose an iron bar, one square inch in section, cooled from 500° C. (a dull red heat) to 0° C. It would, if allowed, contract from a length represented by 1·006 to a length represented by 1, its coefficient of expansion being about ·000012. The bar therefore when at 0° C. is stretched beyond its natural length by $\frac{6}{1000}$ of that length. Now the force capable of stretching a bar of iron of 1 sq. inch section by this amount is about equal to the weight of 15 tons, which therefore represents the force with which it tends to contract. If heated to only 100° C. the force it exerts on cooling will be equal to the weight of about 13 tons, the elasticity of iron being very imperfect when stretched so much.

67. Though the expansion of metals by heat is thus frequently applied to useful purposes it is perhaps more frequently a source of trouble. Thus in order to allow for expansion, the pipes of water and gas mains have to be connected by telescope-joints; the consecutive metals on a railway have to be placed at a small distance apart, and so on. The tubular girders of the Britannia bridge are each mounted on rollers at one end, while the metals are halved together, as shewn in fig. 12, so as to allow a play of about nine inches, without making a gap between them.

FIG. 12.

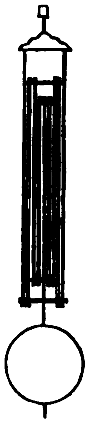


68. Perhaps the expansion of metals causes more trouble to horologists than to any other class of persons. The rate of a clock is usually governed by a pendulum, and the time of vibration of a pendulum depends on the distance between the centres of suspension and of oscillation. Now, if the pendulum consist of a simple metallic rod carrying a weight, when it is heated it expands, and this distance is increased, so that the clock is retarded, while on cooling it is accelerated. A compensating pendulum is one in which the distance between the centres of oscillation and suspension is independent of the temperature.

69. In Graham's mercurial pendulum the bob consists of a glass vessel containing mercury. Now the coefficient of apparent expansion of mercury in glass is very much greater than the coefficient of *linear* expansion of the iron suspension-rod, and while the latter expands downwards, the centre of gravity of the mercury in the glass vessel is raised by the expansion of the mercury, and the quantity of mercury is so arranged that the latter expansion just compensates for the former, and the centre of oscillation remains unmoved. The rod of Graham's pendulum was made of glass, but mercurial pendulums are now usually constructed with iron rods.

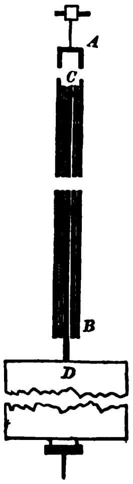
70. Harrison's gridiron pendulum is shewn in fig. 13. The vertical rods there indicated by black lines consist of iron, those shewn by light lines, of which there are four, are made of brass. It is obvious from the construction that the expansion of the iron rods, which are supported at their upper ends, tends to lower the bob, while that of the brass rods, all of which are supported at their lower ends, tends to raise it. Since the coefficient of expansion of brass is, roughly speaking, about 1½ times that of iron, it is obvious that the ratios of the lengths of the brass bars to those of the iron bars, and the distribution of metal throughout the pendulum, can be so arranged as to keep the distance between the centres of suspension and oscillation independent of the temperature.

FIG. 13.



71. A form of pendulum which is much more easily constructed than the gridiron pendulum and answers better, inasmuch as it exposes less surface to the friction of the air, and has its centre of mass much lower down, is shewn in fig. 14. It consists of an iron tube, *AB*, about ¾ in. in diameter, shewn in section in the figure; inside this tube and fitting it loosely is placed a zinc tube which is supported by being rivetted to the iron at *B*. From the top of the zinc tube hangs an iron rod, *CD*, which carries the bob. Here it is obvious that the pendulum will be compensated if *BC* be about equal to $\frac{2}{5}(AB + CD)$, since the coefficient of linear expansion of zinc is about 2½ times that of iron. In order to give sufficient length to the zinc tube, these pendulums are usually constructed so that the point *B* is within a hole drilled through the bob.

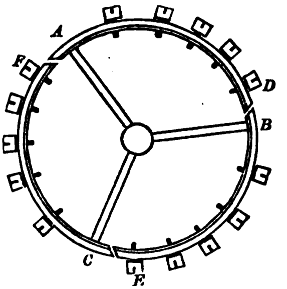
FIG. 14.



72. The movements of watches and chronometers are

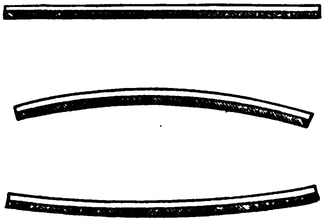
governed by "balance-wheels" which oscillate under the action of the elasticity of the hair-spring, to which they are attached. The time of oscillation of the wheel depends upon its moment of inertia, and increases with it. Now this is increased by increasing the diameter of the wheel, though the mass remains unchanged. Hence a simple balance-wheel will cause the rate of the watch to diminish as the temperature increases. This is obviated in the chronometer balance-wheel shewn in fig. 15, by making the circumference of the wheel of two metals, the outer of which is some metal, as silver, or gold, whose coefficient of expansion is great, while the inner metal is platinum, or some other, whose coefficient of expansion is small. The circumference is cut into two or three parts, each of which is supported at one end by an arm of the wheel. Now, if the temperature increase, the distances of the points *A*, *B*, *C* from the centre of the wheel will increase on account of the expansion of the arms, while the curvature of the arcs *AD*, *BE*, *CF* will increase because the outer metal will expand more than the inner. This will occasion the points *D*, *E*, *F* to approach the centre, and the weights of the heavy screws attached to each arc can be so adjusted that the moment of inertia, and therefore the time of oscillation, of the wheel is unaffected by change of temperature.

Fig. 15.



73. The change of curvature produced in a compound bar, similar to the circumference of the balance-wheel, by change of temperature, may be shewn by rivetting together at an ordinary temperature plane strips of zinc and brass, as in fig. 16, where the brass is shaded. On heating the strip it will assume the second form shewn, while on cooling it in a freezing

Fig. 16.



mixture it will take the third form. This experiment shews conspicuously the difference in the expansion of two metals for the same increments of temperature.

74. Breguet's thermometer consists of very thin strips of silver, gold, and platinum, which are rolled together so as to form a thin narrow ribbon, and this is wound into a helix in which the silver is on the outside and the platinum on the inside. If the temperature of the ribbon increase, the helix winds itself tighter because the expansion of the outside is greater than that of its inner surface, while, when it is cooled, it partially unwinds. If one end of the ribbon be fixed, and a needle or mirror attached to the other end, a very sensitive thermometer is obtained.

CHAPTER V.

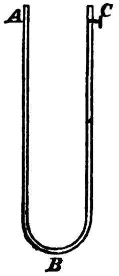
ON THE EFFECTS OF HEAT UPON GASES. THE GASEOUS LAWS. COOLING OF GASES BY EXPANSION. SPECIFIC HEAT OF AIR AT CONSTANT PRESSURE AND AT CONSTANT VOLUME. DIFFUSION OF GASES.

75. WE have now to consider the effects of heat upon gases. A gas has been defined as *a fluid, a finite portion of which can be made to occupy any assigned space, however great, by sufficiently diminishing the pressure to which it is exposed.* In speaking then of the volume of a quantity of gas, it is of primary importance to specify the pressure under which this volume is measured. The law connecting the volume and pressure of a given mass of gas at constant temperature is known as Boyle's, or Mariotte's, law, and is as follows:—

The volume of a given mass of gas at constant temperature varies inversely as its pressure; or, *The product of the numerical measures of the volume and pressure of a given mass of gas at constant temperature is constant.*

76. This may be shewn experimentally by partially filling a tall U tube, *ABC,* with mercury, closing the end *C,* and then pouring mercury into, or out of, the arm *AB.* It will be found that when the air in *BC* has acquired its original temperature after this operation, the volume will vary inversely as the sum or difference of the height of the mercurial barometer and of the difference in

FIG. 17.



height of the surfaces of the mercury in the two arms of the tube, that is, inversely as the whole pressure to which it is subject; the difference of level of the mercury in the arms being added to the height of the barometer when the mercury in *AB* stands above that in *BC*, and subtracted from it when the opposite is the case.

77. The increase in volume of a quantity of air for a given change of temperature when the pressure is kept constant, may be roughly determined by taking an empty thermometer tube, warming it, and, when it begins to cool, dipping the end under the surface of mercury for a very short time, so that a small pellet of mercury may be made to enter the tube. The volume of the air within the instrument will then be determined by the position of the pellet of mercury. This apparatus will serve as an air thermometer for a small range of temperature. By heating the bulb in a bath whose temperature is measured by a mercurial thermometer it will be found that the volume of the air increases very nearly uniformly *for equal increments of temperature indicated by the mercurial thermometer.*

FIG. 18.

78. If the thermometer be filled with any other permanent gas, as Oxygen, Hydrogen, Nitrogen, &c., in a *dry* state, it will be found that the coefficient of expansion is almost precisely the same as for *dry* air, and that for every increase in temperature of 1° C., under any constant pressure, each of these gases expands by about $\frac{1}{273}$ of the volume it would have at 0° C. under the same pressure (though this rate is not quite uniform if the temperature be indicated by the mercurial thermometer). If the volumes of quantities of these different gases, always subject to the same pressure, be equal at some particular temperature, they will also be almost exactly equal when they are all at any other, the same, temperature. Hence, thermometers filled with any of the permanent gases all indicate *the same scale of temperature,* which, however, as stated in

Chapter II., differs very little from that of the mercurial thermometer.

79. From the preceding we see that, if v_0 represent the volume of any quantity of a permanent gas at 0° C., and v_t its volume under the same pressure at t^0 C., then

$$v_t = v_0\left(1 + \frac{1}{273}t\right).$$

Thus if the gas occupied 273 cubic inches at 0° C., it would occupy 274 cubic inches at 1° C., and 373 cubic inches at 100° C. The fraction $\frac{1}{273}$ is often denoted by α.

80. Now suppose that instead of having the air in a bulb tube we have it in a tube of uniform bore throughout and closed at the lower end. Then the volume of the air will be proportional to the distance of the bottom of the pellet of mercury from the bottom of the tube. Suppose that when the temperature is 0° C. the air occupies 27·3 inches of the tube. Let a mark be placed at this distance from the bottom, and called the freezing point. Now place the whole tube in the steam above boiling water, as in the case of the mercurial thermometer described in Chapter II.; it will then be found that the air will occupy 37·3 inches of the tube. Marking the tube at this height, (calling it the boiling point,) and dividing the distance between this point and the freezing point into 100 equal parts, or degrees, each degree will occupy one tenth of an inch of the tube. Marking off distances each equal to the tenth of an inch below the freezing point, and indicating them by the corresponding number with a negative sign prefixed, we find that the bottom of the tube is marked $-273°$. Hence we infer that if the law of contraction of air with decrease of temperature remained the same as at ordinary temperatures, and we could cool the air to a temperature corresponding to $-273°$ C., its volume would be zero. Of course we never expect to realise this, for even supposing it possible to attain this low temperature, which we never hope to do, the air would probably cease to be a gas long before reaching it. The temperature corresponding to the bottom

of the tube is called the *absolute zero* of the air thermometer, and temperatures reckoned from this point are called *absolute temperatures.* The absolute temperature of the freezing point is therefore 273°, and that of the boiling point 373°. Now the volume of the air in the tube at any temperature is proportional to the length of the tube which it occupies, and therefore to the absolute temperature indicated by its upper surface. We see then that,

The volume of any mass of air or other gas at constant pressure increases uniformly with the temperature, and is proportional to the temperature reckoned from the absolute zero of the air thermometer.

This is sometimes called Charles', but more generally Gay Lussac's, law. Boyle's law and this together constitute "the gaseous laws," which should be carefully remembered.

81. *A quantity of gas occupies* 10 *cubic inches at a temperature of* 15° *C.; what will be its volume under the same pressure at* 75° *C.?*

15° C. corresponds to $(273+15)^\circ$, or 288° above the absolute zero of the air thermometer, while 75° C. corresponds to an absolute temperature of 348°.

At 288° Abs. Temp. the gas occupies 10 cubic inches.

$$\therefore \text{ at } 1^\circ \quad \ldots \quad \ldots \quad \text{it would occupy } \frac{10}{288} \text{ cub. ins.}$$

$$\therefore \text{ at } 348^\circ \ldots \quad \ldots \quad \ldots\ldots\ldots \quad \ldots\ldots \frac{10 \times 348}{288} \text{ cub. ins.}$$

$$= 12{\cdot}08\ldots \text{ cub. ins.}$$

This is perhaps the simplest method of finding the relative volumes of a quantity of gas, corresponding to different temperatures.

82. Boyle's law states that the product of the numerical measures of the pressure and volume of a given mass of gas remains constant while the temperature remains so, and we have just seen that if the pressure be kept constant the volume is proportional to the absolute temperature.

Now let v denote the volume, and p the pressure of a quantity of gas whose temperature, reckoned from absolute zero, is T°. Let the temperature be changed to T_1° the pressure remaining the same. Let the volume then become v_1. Then

$$v_1 = v\frac{T_1}{T} \text{ .... } (1),$$

$$\text{and } pv_1 = pv\frac{T_1}{T}.$$

Now let the pressure be increased, the temperature remaining at T_1° till the volume is again reduced to v, and let p_1 denote the pressure when this is the case. Then since the temperature is kept constant,

$$p_1 v = pv_1, \text{ by Boyle's law,}$$

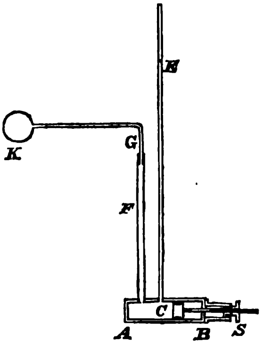
$$\therefore\ p_1 = p\frac{v_1}{v}$$

$$= p\frac{T_1}{T} \text{ by } (1).$$

Now if the gas were heated to T_1°, its volume being kept constant, we should finally have arrived at the same state of things as by the process we have adopted, and the pressure would then, as now, be denoted by p_1. Hence,

The pressure of any mass of gas whose volume is kept constant increases uniformly with the temperature and is proportional to the temperature reckoned from the absolute zero of the air thermometer.

FIG. 19.



83. This result may be tested experimentally by an apparatus designed by Professor Balfour Stewart, the essential portions of which are shewn in fig. 19.

AB is a vessel containing mercury and closed at one end by a piston which can be made to slide in and out through a stuffing box by means of the screw *S*, and thus to change the capacity of the vessel *AB*. *E* is a vertical glass tube communicating with the interior of

AB, and open at the top, while the tube *F* is connected with a very fine tube leading from the glass bulb *K*. The bulb *K* is filled with perfectly dry air, and then attached to *F*. *K* is then cooled to some known temperature, as by placing it in a quantity of melting ice, and the mercury in *F* is made to rise to a marked point *G*, where the tube is very narrow, by turning the screw *S*. The excess of the height of the mercury in the open tube *E* over its height in *F*, when added to the height of the barometer gives the whole pressure to which the air in *K* is subjected. Call this *P*. The bulb *K* is then heated to some known temperature, as, for instance, by placing it in the steam over boiling water, and the piston *C* is advanced by means of the screw *S* till the mercury in *F* again reaches *G*. Determining as before the pressure to which the air in *K* is subjected, and denoting it by *P*, we find that

$$P_1 = P\frac{T_1}{T},$$

where T° and T_1° denote the temperatures of the bulb in the first and second experiments respectively, reckoned from the zero of the air thermometer. If the temperatures employed are those of melting ice and of the steam over water boiling at the standard pressure, we find

$$P_1 = P\frac{373}{273}.$$

84. We see then, that, if the pressure be kept constant, the volume of a given mass of gas varies as its absolute temperature, while if the volume be kept constant the pressure varies as the absolute temperature. Hence, when both volume and pressure are allowed to vary together,

The product of the numerical measures of the pressure and volume of a given mass of gas increases uniformly with the temperature, and is proportional to the temperature reckoned from the absolute zero of the air thermometer.

85. As an example of the application of the preceding laws we may take the following:—

A quantity of air occupies 1 *cubic foot at a temperature of* 59° *F. and under a pressure of* 30·24 *inches of mercury. It is required to find its volume at* 113° *F. under a pressure of* 28·62 *inches of mercury.*

59° F. corresponds to 15° C. or an absolute temperature of 288°, while 113° F. corresponds to 45° C. or 318° C. above the absolute zero of the air thermometer. Hence if the pressure remained constant the volume at 113° F. would be

$$1 \times \frac{318}{288} \text{ cub. feet.}$$

But the pressure changes from 30·24 to 28·62 inches of mercury, and the volume varies inversely as the pressure. Therefore the actual volume is

$$\frac{318}{288} \times \frac{30{\cdot}24}{28{\cdot}62} \text{ cub. ft.} = 1\tfrac{1}{6} \text{ cub. ft.}$$

Or we may proceed thus:—

Volume at 288° under pressure of 30·24 inches is 1 c. ft.

$\therefore$ ... ... 1° .... 30·24 ...... $\dfrac{1}{288}$ c. ft.

$\therefore$ ... ... 1° .... 1 ...... $\dfrac{30{\cdot}24}{288}$ c. ft.

$\therefore$ ... ... 1° .... 28·62 ...... $\dfrac{30{\cdot}24}{288 \times 28{\cdot}62}$ c. ft.

$\therefore$ ... ... 318° .... 28·62 ...... $\dfrac{30{\cdot}24 \times 318}{288 \times 28{\cdot}62}$ c. ft.

86. We have seen that if the volume be kept constant, the pressure of a given mass of gas is proportional to its temperature above the absolute zero of the air thermometer. Hence at the absolute zero of temperature, the pressure of any quantity of gas would be zero, supposing the same law to hold at such a low temperature. Now, according to the molecular theory of gases, a gas consists of a number of very *small particles,* or molecules, moving about with great velocity

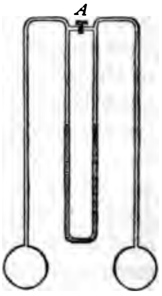
in all directions. The pressure of the gas on any surface in contact with it is due to the continual impacts of these molecules; just as the pressure exerted by the jet of water from a fire-engine is due to the continuous impacts of the particles of water, and it may be readily shewn that this pressure is proportional to the square of the measure of the velocity of the jet, and of the density of the water conjointly. In a similar way it may be shewn that the pressure of a gas upon a surface is proportional to the kinetic energy, or vis-viva, possessed by the unit of volume of the gas. Hence, when this pressure is zero, it follows that the gas possesses no kinetic energy, and that its particles are therefore at rest. This is a reason why the zero of the air thermometer should be considered to be the absolute zero of temperature.

87. We have seen that the coefficient of cubical expansion of the permanent gases at ordinary temperatures is about $\frac{1}{273}$. Gases which, like sulphurous anhydride, are easily liquefied have a somewhat higher coefficient of expansion, and the coefficient is found to increase rapidly as we approach the pressure and temperature at which the gas becomes liquid.

As a general rule gases have a greater coefficient of expansion than liquids, and liquids than solids.

88. The great coefficient of expansion of air renders it useful for the construction of sensitive thermometers. A common form of the differential thermometer is shewn in fig. 20. It consists of a glass tube bent as shewn in the figure, and having a bulb at each extremity. The middle portion of the tube is partly filled with coloured liquid, while the two upper bends are united by a short tube which can be closed by a plug tap, *A*. When *A* is opened the pressures in the two bulbs are equalised, and the liquid stands at the same height in each limb. The tap *A* is then closed. Now if the temperature of the bulbs be initially the same, and if

FIG. 20.



the temperature of either, or both, change, the pressure of the air will be greater in that whose temperature suffers the greater increase, and the liquid will be driven by the excess of pressure towards the other bulb, the difference of the heights at which it stands in the two limbs roughly indicating the difference in the changes of temperature of the two bulbs. If the bulbs differ in temperature when A is closed, the liquid will remain undisturbed provided the absolute temperature of each be increased by a quantity proportional to itself.

89. If a quantity of air be confined in a cylinder into which a piston is accurately fitted, and the piston be suddenly and violently depressed so as to compress the air, the latter will be considerably heated; so much so, that German tinder placed within the cylinder may be ignited, or if a glass cylinder be used, and a little vapour of bisulphide of carbon diffused through the air within it, the vapour may be inflamed, producing a brilliant flash.

90. Suppose a quantity of air heated from T^0 to T_1^0 under constant pressure. Its volume will be correspondingly increased. Now let the air be suddenly compressed to its original volume. Then, as we have just seen, its temperature will be still more increased; lastly, allow the air to cool to the temperature T_1^0, so regulating the pressure that its volume remains unaltered. The air will of course give out heat in cooling, while finally it is in the same condition as if its temperature had been raised from T^0 to T_1^0 in a closed vessel so that its volume was kept constant. We thus see that the amount of heat required to raise the temperature of the air from T^0 to T_1^0 under constant pressure, is greater than the amount required to produce the same rise of temperature when its volume is constant, by the amount of heat given out by the air during the third of the above operations. From this experiment we learn that the *specific heat of air at constant pressure* is greater than its *specific heat at constant volume.* (Dr Joule shewed that the difference was exactly equivalent to the work done by the air in expanding.) If both the pressure and volume were allowed to increase the specific heat would be intermediate between

these two, while if the volume increased so much that the pressure diminished, it would be greater than the first; and if the pressure increased so much that the volume diminished, it would be less than the second.

91. Since gases become heated when suddenly compressed, it will follow that, if allowed to expand, by relieving the pressure, the gases will be cooled, provided they do not receive heat from without. We shall meet with instances of this in Chapter IX.

92. If a quantity of gas be allowed to expand without doing any external work, as when it expands into a vacuum, no heat is lost or gained by the gas as a whole. This was shewn by Dr Joule, who connected a vessel containing compressed air, with a second vessel which was exhausted, the communication between them being closed by a tap. The two vessels were placed under the water in a calorimeter, and after they had acquired the temperature of the water, the tap was opened. The temperature of the water remained unaffected. Hence when air expands without doing external work, no heat is lost or gained by it. The air left in the first vessel did work in driving the air into the second with great velocity, and was itself cooled, but the air entering the second vessel on striking against its sides acquired as much heat by the impact as was lost by that in the first, so that as much heat was communicated to the water by one vessel as was taken from it by the other.

93. In Art. 46 we explained how the specific heats of air, and other gases, at constant pressure, were determined by Regnault. The results of his investigations may be summed up in the following laws.

1. *The specific heat of a permanent gas at constant pressure is independent of that pressure, and the same for all temperatures.*

2. *The capacity for heat of* EQUAL VOLUMES *of different permanent gases at the same pressure and temperature are equal.*

3. *The specific heats of the easily condensible gases vary slightly with the temperature.*

The experimental determination of the specific heat of air at constant volume is one of extreme difficulty. An indirect method by which this has been effected will be described in Chapter X. We may, however, here remark that, for all the permanent gases, the ratio of the specific heat at constant pressure to that at constant volume is independent of the temperature of the gas, and for air is about 1·41.

DIFFUSION OF GASES.

94. If two vessels containing different gases be allowed to communicate with each other for some time, it will be found that each vessel contains a mixture of the gases of the same composition, and this will be the case even if one of the gases be much denser than the other, and the vessel containing it be placed at a considerable distance below that containing the lighter gas, the communication being made by a tube. Oxygen may be used for the heavier, and hydrogen for the lighter gas, and the mixtures subsequently exploded.

This phenomenon is known as *the diffusion of gases,* and in virtue of it the atmosphere has nearly the same composition at all heights to which men have ascended. It is sometimes expressed by saying that one gas acts as a vacuum to another.

95. If, in accordance with the molecular theory of gases, we suppose that a gas consists of a number of very small particles moving in all directions with great velocities, we see that they will penetrate into any space which is open to them, and the presence of any other gas in that space will only delay their diffusion throughout it by causing them to continually come into collision with its own particles, just as the passage of a person through a crowd is impeded by the presence of others, and would be much more so were all the persons composing the crowd, and including the intruder, highly elastic and perfectly devoid of intelligence. The molecular theory of gases thus readily accounts for the phenomenon of diffusion, and we see that either gas will ultimately be uniformly distributed throughout each vessel, because it is only then that the number of its particles pass-

ing from the first to the second vessel in any given time will be equal to the number passing in the opposite direction.

The molecular theory of gases also teaches us that the squares of the velocities of the particles of different gases under any given pressure vary inversely as the density of the gas, and this accounts for the law discovered by Graham, that gases diffuse into one another at rates varying inversely as the square roots of their densities.

96. The expansion of gases has been turned to practical account in the construction of pyrometers, or instruments for measuring very high temperatures, as of furnaces. Of these Regnault's mercury pyrometer may be taken as an example. It consists of a bottle of iron, platinum, or porcelain, the neck of which has a narrow opening, and is covered by a lid whose diameter is considerably greater than its own. The lid has a small hole bored through it, and the top of the neck and lower surface of the lid are ground together, so that by sliding the lid on the neck the bottle may be opened or closed. A small quantity of mercury is placed in the bottle, and the whole placed in the furnace. The quantity of mercury must be sufficient to expel, when volatilised, all the air from the bottle, and when it has acquired the temperature of the furnace the neck is closed by sliding the cover, and the instrument removed and allowed to cool. When cold the mercury within it is weighed, and this gives the weight of mercury vapour which filled the bottle at the temperature of the furnace. The capacity of the bottle is determined by weighing it when full of mercury, and weighing it when empty. Then if we know the height of the barometer, and the specific gravity of mercury and of mercury vapour at any temperature and pressure as well as the law of expansion of mercury vapour, we can calculate the temperature of the furnace.

Suppose for example that the amount of liquid mercury at 15°C. required to fill the bottle is 314 ozs., and that at this temperature a cubic foot of mercury weighs 13564·8 ozs. Then it follows that the capacity of the flask is 40 cubic inches. Suppose also that the amount of mercury left in the bottle after being removed from the furnace is 13 grains, and that at 360°C. a cubic foot of mercury vapour weighs

1580 grains, when under the same pressure as during the experiment. Then if the temperature of the furnace be T° C. 40 cubic inches of mercury vapour will weigh

$$1580 \times \frac{40}{1728} \times \frac{360+273}{T+273} \text{ grains,}$$

supposing mercury vapour to behave as a perfect gas at temperatures above 360° C. But

$$1580 \times \frac{40}{1728} \times \frac{360+273}{T+273} = 13,$$

therefore $$T+273 = \frac{1580 \times 40 \times (360+273)}{1728 \times 13}$$

$$= 1779{\cdot}7\ldots$$

therefore $$T = 1506{\cdot}7\ldots$$

and the temperature of the furnace is 1506·7°C.

97. In Wedgwood's pyrometer the temperature is measured by the contraction of a piece of baked clay; others have been constructed in which the temperature is indicated by the expansion of a platinum bar. The action of Siemens' pyrometer depends upon the increase of the resistance which platinum wire offers to the passage of an electric current as its temperature is raised. It consists of a very fine platinum wire wound on a small porcelain bobbin, the ends of the wire being attached to very thick wires whose resistance is exceedingly small compared with its own. The bobbin is placed within the furnace, with the thick wires leading from it to any convenient place, and the resistance of the wire is then measured in the usual way, and the temperature of the furnace deduced.

CHAPTER VI.

ON THE EFFECTS OF HEAT IN PRODUCING CHANGES OF STATE IN BODIES. LATENT HEAT. REGELATION. BOILING AND EVAPORATION. DEW-POINT. SPHEROIDAL STATE. THERMO-ELECTRIC PILE.

98. IF heat be made to enter a solid body its temperature will, in general, be increased, and the solid will expand, until it arrives at a certain temperature (which depends for each solid only on the pressure to which it is subjected) called the fusing point, when the solid will begin to liquefy, and the temperature will remain unchanged till the whole of the solid is converted into the liquid state. During this process the volumes of most bodies increase, but there are many substances which, like ice, cast iron, and many alloys, contract on fusing and expand during solidification, and this enables sharp castings to be taken in these materials.

99. During the process of liquefaction the application of heat has to be continued, and a large amount is absorbed by the melting body. This heat has no effect upon the *temperature* of the body, which, as we have said, remains constant till the whole is liquid. On this account the heat absorbed during this process was said to become *latent,* and was called the *latent heat of fusion.* It may be thus defined:—

DEF. *The latent heat of fusion of a substance is the number of units of heat absorbed by the unit of mass of the substance in passing from the solid to the liquid state without increase of temperature.*

In Chapter III. we saw that a pound of ice in melting at 0° C. would cool a pound of water from 79° C. to 0° C. The latent heat of fusion of ice, or, as it is more generally called, the latent heat of water, is therefore 79.

100. The phrase "latent heat" is not well chosen, because the heat absorbed during liquefaction does not remain within the substance as hidden heat, or heat insensible to the thermometer, but actually ceases to be heat, being used up in doing *internal work;* just as when a steam crane is employed in lifting building stones, part of the heat generated in the furnace ceases to be heat, being used up in doing work, and having its representative in so many tons of material lifted so many feet against the attraction of the earth.

101. When the whole of a solid has been converted into liquid, if the application of heat be continued, the temperature of the liquid will begin to rise, while its volume will generally increase, until it reaches a certain temperature depending for each liquid only on the pressure to which it is exposed, and called the *boiling point* corresponding to that pressure. The liquid will then pass off rapidly into the state of vapour, or gas, and the temperature will cease to rise while there is any liquid left. If the vapour be collected in a vessel, and heat applied, its temperature will continue to rise till we reach the limits of our heating power, and no further change of state will generally take place, unless chemical decomposition, or dissociation, occur. During the conversion of the liquid into the gaseous state, a large amount of heat is absorbed without any corresponding increase of temperature. Part of this heat is consumed in lifting the air above the liquid, and another part in doing work against molecular forces which oppose the motion of the particles of steam when passing across the boundary of the liquid and the air. The heat so absorbed is called the *latent heat of evaporation.*

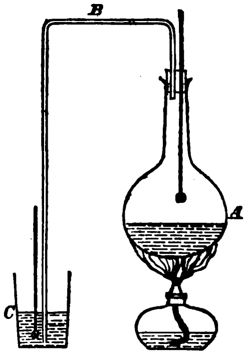
102. DEF. *The latent heat of evaporation of a substance at any temperature is the number of units of heat absorbed by the unit of mass of the substance in passing from the liquid to the gaseous state at that temperature.*

DEF. *A liquid is said to boil when the pressure of its vapour is equal to the external pressure to which it is exposed.*

DEF. *The boiling point of a liquid is that temperature at which the pressure of its vapour is equal to the standard atmospheric pressure.*

103. There are a few substances which, like arsenic and iodine, pass at once from the solid to the gaseous state without passing through the intermediate liquid condition, and which can only be liquefied by heating them under a pressure considerably greater than that of the atmosphere. There are other substances which, like camphor, though they can be liquefied under ordinary atmospheric pressure, evaporate more or less readily from the solid condition without becoming liquid. Ice is one of these; and during a long frost, when the air is dry, snow slowly evaporates without thawing.

FIG. 21.



104. The latent heat of evaporation of water, more generally called the *latent heat of steam*, may be measured by means of the apparatus shewn in fig. 21. *A* represents a flask containing boiling water, the steam from which escapes through the tube *B*; *C* is a beaker containing a known weight, say 1000 grains, of distilled water at a known temperature, say 14° C. When the steam is escaping freely from *B*, its end is made to dip nearly to the bottom of the water in the beaker. After a short time the tube *B* is removed, and the temperature of the water in the beaker observed. Suppose it to be 20° C. The beaker is then weighed, and the difference between this and the last weighing gives the amount of steam which has entered it. Suppose this to be 10 grains, and suppose the temperature of the steam, as indicated by the thermometer in *A*, to be 100° C. The 10 grains of steam in being cooled from 100° C. to 20° C., have raised the temperature of 1000 grains of water 6° C. Ten grains of steam therefore in condensing and cooling from 100° C. to 20°., emit as much heat as would raise 6000 grains of water 1° C. But 10 grains of water in cooling from 100° C. to 20 C., would emit sufficient heat to raise 800

grains of water 1° C. Hence 10 grains of steam at 100° C., in condensing to water at 100° C., emit sufficient heat to raise 5200 grains of water 1° C. The latent heat of steam is therefore determined by this experiment to be 520.

105. The result obtained in the last article is, obviously, too small, because we have neglected the heat taken up by the beaker as well as that lost to surrounding bodies. This source of error may be eliminated by emptying the beaker after the last weighing, placing in it 1000 grains of water at 14° C. as before, and slowly pouring into this a quantity of water at some known temperature, say 50° C., keeping the whole well stirred until the temperature of the water in the beaker is 20° C., the same as after the entrance of the steam. If about the same time be occupied in this process as in the admission of the steam, about the same amount of heat will be lost to surrounding bodies, and the same amount will be taken up by the beaker. Suppose the amount of water at 50° C., which has been poured in, to be 206 grains. Then since the 206 grains of water at 50° C. have produced the same effect as was produced previously by the 10 grains of steam, it follows that 10 grains of steam at 100° C., in becoming water at 20° C., give out as much heat as 206 grains of water in cooling through 30° C., or as much as would raise 6180 grains of water 1° C. Whence we get for the latent heat of steam the number 538. Its actual value at 100° C. is about 537.

106. While the steam is entering the water in the calorimeter a loud noise is heard similar to that produced in the tender of a locomotive when the waste steam is made to enter the tank. This is due to the successive collapses of bubbles of steam as they are condensed by the water. The *singing* of a kettle is produced by the same cause, bubbles of steam being formed in contact with the hot bottom of the kettle, and collapsing as they enter the colder water above. The singing always ceases when the water begins to boil.

107. The temperature at which liquids boil varies very much with the pressure to which they are exposed. The temperature of the water in the boiler of a locomotive when *the pressure* of the steam is about nine times that of the

atmosphere, is between 170° C. and 180° C., while the temperature of water boiling in the open air at the top of Mont Blanc is not much above 82° C. In order to raise water to temperatures above the boiling point corresponding to atmospheric pressure, the water must be confined in a high-pressure boiler, to which a safety-valve, allowing the escape of the steam before it attains a dangerous pressure, should be attached. Papin's digester consists of a vessel of this nature, and is used for dissolving gelatine, &c., from bones, an operation which requires the action of water at a temperature considerably above 100° C. Similarly, good tea cannot be made at great elevations without an apparatus of this description on account of the high temperature required.

108. The temperature at which water boils depends very much on the nature of the vessel in which it is heated, on account of a peculiar resistance offered by the water to any break in the continuity of its mass, such as would be occasioned by the formation of steam within it. If the water be freed from air by long boiling, and be placed in a perfectly clean glass vessel, it may be raised to a temperature considerably above the boiling point corresponding to the pressure to which it is exposed. The introduction of a piece of metal, or of various other substances, will then occasion an explosive discharge of steam, and the temperature of the water will be reduced to the *boiling point.* The temperature at which water boils is also affected by its containing foreign matter in solution. The temperature of the steam above the surface of the water is, however, *always the same under the same pressure.*

109. From this it follows that if we can determine the temperature of steam above the surface of boiling water at any place, we may find, by reference to tables constructed for the purpose, the barometric pressure to which it is subjected. The *hypsometer*, described in Art. 24, enables us to do this, and may therefore be employed instead of a barometer for the determination of the heights of mountains. It is from its employment for this purpose that the instrument derives its name.

110. In the same way as, and for the same reason that, pure water can be heated above the boiling point, it can also

be cooled below the freezing point without solidifying; but on disturbing the water by the introduction of certain foreign bodies, crystals of ice are formed in a network throughout its mass, and the temperature of the whole is raised to 0° C. The temperature of pure ice while melting is always 0° C. under ordinary pressure. The melting point of ice is, however, lowered by increase of pressure; and Professor James Thomson has shewn that whenever a body expands (like water) on solidification, its melting point is *lowered* by increase of pressure, while if it (like wax) contract, its melting point is *raised* by the same means.

111. If two pieces of dry ice be pressed together, and the pressure be then relieved, they will be found to be frozen together. If the temperature of the ice be not sensibly below 0° C., a very slight pressure will be sufficient to produce this effect. If two pieces of ice are floating in warm water, and come in collision with each other so as to be in contact over a small area only, they will readily freeze together. In these cases the pressure lowers the freezing point, and consequently melts some of the ice; on relieving the pressure, some of the water formed again freezes, and unites the two blocks. This process is called *regelation.* It is in virtue of this property of ice that the *crevasses* formed in a glacier while passing a bend in its valley are completely obliterated when passing a bend in the opposite direction.

The effect of regelation may be shewn by compressing a quantity of pounded ice in a mould of hard wood, by means of a Bramah press. Some of the ice melts until the heat absorbed in this process has reduced the temperature of the whole to the freezing point at the pressure to which it is exposed, and during this process part of the water escapes, and the remainder is thus deprived of some of its heat. On relieving the pressure the mass in the mould freezes into a hard solid block at a temperature below 0° C. In this way beautiful lenses, cups, &c., can be formed in ice.

112. The action of freezing mixtures depends on the heat absorbed by solids in liquefying or by liquids in evaporating. If salt be mixed with pounded ice the affinity of *salt for water* compels the ice to melt, and in so doing the

latent heat of liquefaction is absorbed. In this way a temperature of about -18° C. can be readily obtained.

By mixing ether with nitrous anhydride which has been liquefied by cold and pressure, and allowing the mixture to evaporate in vacuo, a temperature estimated at -140° C. has been obtained.

113. The latent heat of steam depends upon the temperature at which it is produced, and is less the higher the temperature, so that the latent heat of steam generated in a high-pressure boiler is considerably less than that of steam generated at ordinary pressure, which is itself less than the latent heat absorbed during the evaporation of water at the ordinary temperature of the air; the latent heat of water, on the other hand, is less the lower the temperature at which the ice is melted. These statements may be proved experimentally, or may be considered to follow from the fact that the specific heat of water is greater than that of either steam, or ice, the specific heat of steam at constant pressure being about ·48, and that of ice about ·5.

If the latent heat of steam continue to decrease as the pressure, and therefore the temperature, at which it is produced, are raised, we shall at last arrive at a temperature at which the latent heat is zero. If water be heated in a sealed tube, which it partially fills, we at last reach a temperature at which the liquid and the steam above it seem to pass insensibly into each other, the bounding surface between them vanishing, and the whole mass appearing to be quite homogeneous. The temperature at which this occurs is called the *critical point*. This phenomenon was discovered by Dr Andrews, and has been observed by him in carbonic anhydride and several other liquefiable gases.

114. We have said that the temperature at which a liquid boils depends upon the pressure to which it is exposed, and have defined the boiling point of a liquid as that temperature at which the pressure of its vapour is equal to the atmospheric pressure. If the temperature of the liquid be sensibly higher than this, vapour will be generated throughout its mass, and the liquid will boil violently. If the vessel

containing the liquid be open, the boiling will continue as long as there is any liquid present at a temperature above that at which it can boil under the atmospheric pressure, but if the liquid be in a closed vessel its own vapour will increase the pressure upon it, and presently the boiling will cease provided the temperature be kept constant.

If there be no air, or gas other than the vapour of the liquid, above its surface, the whole pressure on the free surface of the liquid is due to the pressure of its vapour, and the amount of vapour in the unit of volume will therefore be that which is capable of exerting this pressure at the temperature of the enclosure. Since the pressure under which liquids boil increases very rapidly with the temperature, much more so than the pressure of a given mass of vapour at constant volume, it follows that the density of the vapour above the surface of the liquid will increase rapidly with the temperature.

115. If a quantity of warm water at a temperature considerably below 100° C. be placed under the receiver of an air-pump, and the air rapidly removed, the water will boil violently, shewing that the temperature at which water boils is lowered by diminution of pressure.

The same may also be shewn in a striking manner by boiling a quantity of water in a glass flask until the air above it has been expelled by the steam, corking the neck of the flask, and pouring a stream of cold water over it. The water in the flask will then be seen to boil vigorously. In this case, the steam in the upper part of the flask is cooled much more than the mass of water below it. Its temperature is therefore reduced below the boiling point corresponding to its pressure, and part of the steam is consequently condensed. On account of this, the pressure on the surface of the water is diminished, but the temperature of the water is, for some time, only slightly lowered by the stream outside, hence its temperature is sensibly above the boiling point corresponding to the pressure on its surface. The water therefore boils violently, the steam produced being in its turn condensed; and this process can be carried on for a considerable time.

116. Now suppose that a quantity of liquid is placed in a closed vessel, and that there is *air* above its surface. Suppose also that the temperature of the water is sensibly above the boiling point corresponding to the pressure of the air above it, and is kept constant. The liquid will then boil violently until the pressure on its surface is such that the corresponding boiling point of the liquid is the temperature it possesses. When this stage is reached, the pressure on the liquid is the sum of the pressures exerted by the air and by its own vapour, and the greater the pressure of the air the less will be the amount of vapour per unit volume *when the liquid just ceases to boil.*

It is found however by experiment that the formation of vapour in a closed vessel, when air, or any gas other than the vapour, is present, does not stop when the liquid ceases to boil, but *goes on until the pressure exerted by the vapour alone is that pressure under which the temperature of the liquid is its boiling point.* During this process no bubbles of vapour are formed in the liquid, as is the case during boiling, but the vapour appears to be quietly formed at the surface. This mode of transition from the liquid to the gaseous state is called *Evaporation.*

117. From what has just been said, it appears that a liquid will go on evaporating till the pressure of its vapour alone reaches a certain value *depending only on the temperature,* and independent of the presence of any amount of other vapours, or gases, in the same space. Thus, if a quantity of water be placed in a closed vessel with dry air above it, though the pressure of the air may be far too great to allow of the water boiling, nevertheless vapour will be formed till the amount above the water is the same as if no air had been present, the only difference being that in the case we have supposed the whole of the vapour is produced by slow *evaporation,* while if the water had been placed in vacuo its formation would have been much more rapid and accompanied with *ebullition.* We also see that the pressure on the water will finally exceed that exerted by the air, however great this may be, by a quantity depending only on the temperature. This is sometimes expressed by saying that different gases and vapours act towards one another as vacua.

It should be observed that no distinction can be drawn between gases and vapours, the term vapour being generally applied to the gas of a substance which is capable of existing in the liquid form at ordinary temperatures and under ordinary pressures. Most of what are usually called gases, may, however, be liquefied by cold and pressure. Steam, or aqueous vapour, may therefore properly be called water-gas.

118. The pressure which the vapour of any volatile liquid can exert at any temperature below its boiling point under atmospheric pressure, may be measured by introducing a small but sufficient quantity into the tube of a mercurial barometer. Part of the liquid rising to the surface of the mercury evaporates in the Torricellian vacuum, and the pressure of the vapour produces a corresponding depression of the column. The liquid is of course cooled by the evaporation, and time should be allowed for it to acquire the temperature of the surrounding space before measuring the depression. The instrument may be kept at the desired temperature by immersion in an air-bath.

If a quantity of dry air or other gas be allowed to enter a barometer tube, the mercury will of course be depressed; if a little volatile liquid be then inserted, as in the last experiment, it is found that the mercury is further depressed by exactly the same amount as if no air had been present. This shews that the pressure of the vapour, and therefore the amount per unit of volume, is independent of the presence of the air.

119. DEF. *When the amount of any vapour in a space is the greatest that can exist in it without increase of temperature, the space is said to be saturated with the vapour.*

DEF. *The temperature at which any space is saturated with the aqueous vapour it contains is called its Dew-point.*

If the temperature in a space containing an amount of aqueous vapour insufficient to saturate it, be lowered, the space will at length become saturated, and the corresponding temperature is the dew-point. On still further lowering the temperature, condensation of part of the vapour takes place and the space remains saturated.

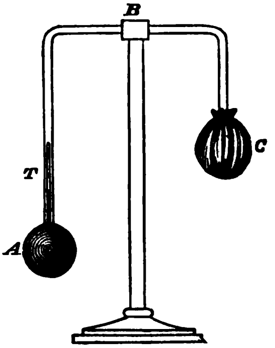
120. From what has been said it will be seen that air in the presence of water must contain a quantity of aqueous vapour, and thus all the air around us contains more or less vapour, some of which will be condensed if the air be sufficiently cooled, condensation commencing when the dew-point is reached.

If we have a table giving us the pressure of aqueous vapour for different temperatures in a space saturated with it, or, what is the same thing, the boiling point of water corresponding to different pressures, the determination of the amount of aqueous vapour in any volume of air may be reduced to a determination of the dew-point. The determination of this point is therefore a matter of considerable importance, and several instruments have been constructed for the purpose.

121. A simple form of dew-point instrument consists of a metal box covered with a piece of polished black glass, a thermometer being placed with its bulb in close contact with the glass. A stream of cold water, whose rate can be regulated at pleasure, is made to flow through the box, and when a film of moisture begins to dull the polished surface of the glass, the stream is stopped and the thermometer read. In a few seconds the cloud will begin to leave the glass, and the thermometer is again observed. The mean of the two temperatures is approximately the dew-point.

122. Daniell's dew-point instrument, frequently called Daniell's hygrometer, is shewn in fig. 22. A bulb *A* made of black glass is connected with the bulb *C* by the tube *ABC*, of clear glass. The bulb *A* contains a quantity of liquid ether, into which dips the bulb of a small thermometer *T*. The whole apparatus is exhausted of air before being sealed, so that the bulbs contain only ether and its vapour. The bulb *C* is covered with muslin or similar

FIG. 22.



material, and when the instrument is to be used liquid ether is poured over the muslin. This evaporates and in so doing absorbs the latent heat of evaporation, cooling the bulb and causing the ether vapour within it to condense, thus diminishing the pressure within the tube. This causes the ether in *A* to evaporate with a consequent lowering of the temperature of *A*, and after some time moisture begins to be deposited on the outside of the bulb. The thermometer *T* is then observed and the muslin on *C* is allowed to become dry. The temperature of *A* will then gradually rise, and when the dew upon it begins to disappear, the temperature of *T* is again observed. The mean of the two readings of *T* is taken as the dew-point.

123. Mason's dry and wet bulb thermometers are frequently used for determining the amount of moisture in the air. They consist of two thermometers mounted side by side, the bulb of one being exposed while that of the other is covered with lamp-cotton, or muslin, kept wet by dipping one end into a vessel of water, when the water rises in the cotton, as spirit in the wick of a lamp, and the bulb of the thermometer is thus kept wet. Now if the air be far from saturated with moisture, the water will evaporate rapidly from the cotton, and in doing so will cool the bulb of the thermometer below the temperature of the air, the amount of such cooling being less the more nearly the air is saturated. Empirical formulæ have been employed for the determination of the dew-point from the temperatures indicated by the thermometers, and if the current of air to which the instrument is exposed be gentle, the method admits of considerable accuracy.

The determination of the dew-point, or of the amount of moisture in the air, is called hygrometry, and instruments employed for this purpose are sometimes called hygrometers, but more properly Dew-point instruments.

124. As an example illustrating this subject we may take the following:—

Find the weight of dry air in a cubic foot of air containing aqueous vapour at 15° *C. under a pressure of* 30 *inches of mercury, when the dew-point is* 10° *C., it being given* *that a cubic foot of dry air at 0° C. and under the above pressure weighs 554 grains, and that the pressure of aqueous vapour in a space saturated with it at 10 C. is equal to the pressure of ·36 in. of mercury.*

The amount of aqueous vapour in the cubic foot is such that at 10° C. it would exert a pressure equal to that of ·36 in. of mercury. Therefore by Gay Lussac's law (see Art. 80) at 15° C. it exerts a pressure of $\cdot 36 \times \frac{288}{283}$ in. of mercury, $= \cdot 3663\ldots$ in. of mercury. The pressure exerted by the dry air occupying the same volume is therefore equal to that of $30 - \cdot 3663$ in. of mercury, $= 29\cdot 6337$ in. of mercury. Hence the volume which the dry air would occupy under a pressure of 30 inches of mercury at 15° C. is $\frac{29\cdot 6337}{30}$ cub. ft., and the volume it would occupy at 0° C. under the same pressure is $\frac{29\cdot 6337}{30} \times \frac{273}{288}$ cub. ft., and its weight is therefore $554 \times \frac{29\;6337}{30} \times \frac{273}{288}$ grains,

$$= 518\cdot 73 \text{ grains, nearly.}$$

125. When the temperature of a liquid is so high that the pressure of its vapour is greater than that of the atmosphere, this pressure may be measured by heating the liquid in a closed boiler, to which any convenient form of pressure-gauge is attached. For accurate measurement a number of U tubes, each containing some mercury, are connected together in succession, and the first of the series made to communicate with the boiler. The pressure in the boiler will then be found by adding the height of the barometer to the sum of the differences of level of the mercury in the two arms of each tube.

126. The fact that the amount of aqueous vapour capable of existing in a cubic foot, or other definite amount, of space above the surface of water, is independent of the presence of any other vapours or gases, is explained by the molecular theory in the following way.

The theory supposes that liquid water consists of a number of particles moving with different velocities in all directions, but so acting on one another as to be continually interfering with each other's motions. It also supposes that the vapour consists of a number of particles also moving with various velocities, but not interfering with one another until they come very close together, when repulsion takes place between them. The velocities both of the particles of gas, or vapour, and of those of water, are increased with increase of temperature. The theory also supposes that there is a force acting for a very small distance on each side of the bounding surface of the liquid and gas, tending to prevent the escape of particles from the liquid. If a particle of liquid is moving towards the surface with sufficient velocity, it will have sufficient energy to carry it right through this field of force, and will then be free in space, and, in fact, will be a particle of gas. Now we have said that increase of temperature increases the velocity of the particles of liquid, and it will therefore increase the number which will escape from any surface of the liquid in a second. This number will therefore depend upon the temperature of the liquid, and be also proportional to its surface. Now of the particles of gas outside, some will be moving towards the liquid with considerable velocity, and will enter the liquid, where they will be, as it were, taken prisoners by the other particles, and ceasing to be particles of gas will become part of the liquid. Also, the number of these which enter the liquid per second will be proportional to the extent of the surface of the liquid and *to the number of particles of gas in the unit of volume above it.* It will also depend on the temperature of the gas. Now *when the number of particles of liquid which escape from each unit of area of its surface is equal to the number of particles of the gas which enter it through the same area, the number of particles of gas above the liquid will remain unchanged,* in fact the space will then be saturated with the vapour, and it may be shewn that this final state of things, or balance of exchanges, will not be affected by the presence of foreign particles with the vapour.

127. It may be of use to briefly trace out the changes which take place in a mass of ice as it is gradually heated.

Suppose we have a pound of ice at, say, $-20°$ C. Then, *when heated, it* expands, its coefficient of cubical expansion being about ·00012 per 1° C., and its specific heat about ·5. It will thus absorb about 10 units of heat, while its temperature is raised to 0° C., before it begins to melt. The substance will then remain at this temperature till it has absorbed about 79 units of heat, when it will all have been converted into water, and in the transition its volume will have contracted by about 9 per cent. The temperature will then go on increasing steadily, the water contracting in bulk till its temperature reaches 4° C., after which it will continue to expand until about 100 units of heat have entered the water, when its temperature will be 100° C., and its volume will have increased by rather more than 4 per cent. of its volume as water at 0° C. The water will then begin to boil, and if the heat be continued, the whole will pass off as steam, absorbing in the process about 537 units of heat, and expanding to about 1600 times the volume of the water, the barometer being supposed to stand at 30 inches. Thus the amount of heat absorbed in the transformation of a pound of ice at – 20° C. to steam at 100° C. is

$$10 + 79 + 100 + 537 \text{ units} = 726 \text{ units},$$

or as much as would raise 726 pounds of water 1° C.

FIG. 23.

128. If a small quantity of water or other volatile liquid be dropped upon a metal plate heated to a temperature very considerably above the boiling point of the liquid, vapour will be generated from the lower surface of the drop at such a rate as to prevent the liquid from coming into contact with the metal. In fact the drop will be supported on an elastic cushion formed of its own vapour, and a beam of light may be made to pass between the drop and the plate. The liquid is then said to be in the *spheroidal condition.* If the temperature of the plate be allowed to fall, the vapour will presently be produced too slowly to support the liquid, which will come into contact with the metal, and pass into vapour suddenly with explosive violence.

If a quantity of solid carbonic anhydride be dissolved in ether and poured into a white-hot platinum crucible, it will be kept from contact with the metal in the same way, while such intense cold will be produced by its evaporation, that a spoonful of mercury placed within it will be frozen, and may be removed in the solid form.

THERMO-ELECTRICITY.

129. While treating of the effects of heat upon bodies we may mention, that if two bars of different metals be united at each end so as to form a closed circuit, and if one of the junctions be heated above the other, an electric current will be produced in the circuit. If the metals be copper and iron, the current will flow from the copper to the iron through the heated junction, and the other junction will become heated by its means, while if the junctions be initially at the same temperature and a current from a battery be made to traverse the circuit, the junction at which the current passes from copper to iron will be cooled, while that at which it passes from iron to copper will be heated, as above. If bismuth and antimony be used instead of copper and iron, still more powerful effects are produced by small differences of temperature.

130. If several bars of bismuth and antimony are united, as in the figure, and the alternate junctions heated, the electromotive force in the circuit is the sum of the forces due to each pair of consecutive junctions, and by using a large number of bars a very sensitive instrument may be constructed. The thermo-electric pile consists of a number of such bars united in the form of a cube, the alternate junctions being on opposite faces. If the extreme bars are united by a wire passing round a freely suspended magnetic needle, any difference in the temperatures of the opposite faces of the cube at which the junctions are situate, produces a corresponding deflection of the needle, the pile thus acting as a very delicate differential thermometer. One of the faces of such a *pile is shewn in fig. 25.*

FIG. 24.

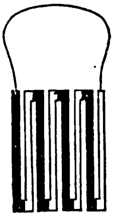
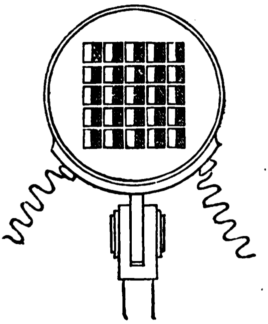


FIG. 25.



CHAPTER VII.

ON THE TRANSMISSION OF HEAT.

131. THERE are three methods generally enumerated by which heat may be transmitted from one point to another. They are,

I. *Conduction.*
II. *Convection.*
III. *Radiation.*

Heat is said to be transmitted by conduction when it passes from hotter to colder portions of the same body, or from a hot body to a colder body in contact with it: the heat in this case being transmitted from each particle of the material of the body to *contiguous* particles in directions in which the temperature decreases. A familiar example of conduction is found in the transmission of heat along a poker, one end of which is placed in the fire.

Heat is transmitted by convection when the material body containing the heat is carried from one point to another.

Thus if hot water is carried in a bucket or conveyed in pipes from one point to another, the heat contained in the water, as well as the water itself, is said to be transmitted by convection.

Heat is said to be transmitted by radiation when it passes from one point to another without heating the medium through which it passes.

Thus we feel the sun's rays to be warm, and a thermometer exposed to them will indicate a temperature considerably above 0° C., though the air through which the rays pass may be at a temperature below the freezing point. Bodies which, like air, allow of the passage of radiation through them without themselves becoming heated, are called

Diathermanous, while bodies which, like the metals, do not possess this property are called Adiathermanous.

132. The last mode of transmission of heat differs from the two preceding, inasmuch as the heat does not pass from one point to another *as heat,* but is converted into another form of energy which is only reconverted into heat under special circumstances; and in some cases is capable of causing the sensation of light if allowed to enter the eye, or even of producing a photographic picture on a properly prepared surface, by inducing chemical or molecular changes in the constitution of the body on which it falls. The transmission of heat by radiation is therefore a case of double *transformation of energy,* and may be classed with several other ways in which heat appears to be communicated from one place to another, though, during its passage, it is really not heat at all; as, for example, when some of the heat generated in the furnace under the boiler of a steam-engine is converted into the energy of motion of the parts of the machinery, and partially reconverted into heat by the friction of the bearings, &c.; or, when the heat applied to one set of junctions in the thermo-electric pile, is converted into the energy of an electric current, and reconverted into heat at the opposite set of junctions, and in the wire through which it passes.

133. If we enter a very cold room, and touch various articles in the room, we find that the metal articles feel coldest of all, and of these we may notice that large masses of silver or copper feel especially cold to the touch, while the wooden furniture produces the sensation of cold in a less degree, and the hearth rug, or other woollen materials, hardly seem cold. Now if a thermometer be brought into contact with all these articles in succession it will register the same temperature, the reason of the difference to the touch being, that the metal bodies transmit heat through their own mass, and so take it away from the hand, much more readily than wood, and wooden articles much more readily than woollen materials. In fact, the bodies which feel colder than others, seem so, not because they are at *lower temperatures,* but, because they are better conductors

of heat. In high latitudes, where the cold is very intense, contact with a piece of metal exposed to the weather will inflict a blister on the hand.

For a reason similar to the above, in the hot room of a Turkish bath, metal objects feel much hotter than others, and will inflict a burn, so that spectacles with metal frames have to be dispensed with. The human body is prevented from being unduly heated by the evaporation going on from its surface.

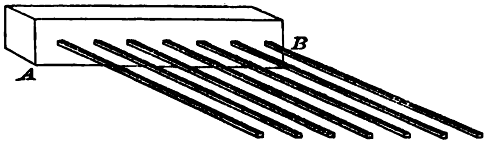
134. From what we have just said we see that different bodies possess different powers of conducting heat.

DEF. *The power which a body possesses of conducting heat is called its thermal conductivity.*

The fact that there is a difference in the thermal conductivity of different substances, may be readily shewn by taking three tea-spoons, made of silver, lead and bone respectively, and placing their bowls in hot tea. The handle of the silver spoon soon becomes too hot to touch without inconvenience, and in the same time that of the leaden spoon becomes hot, but less so than than the former, while the handle of the bone spoon is only slightly heated. Silver spoons may be distinguished from those made of other metals and plated, by the readiness with which they transmit the heat of the tea to the hand. It is on account of the low conductivity of such substances as wood, bone, glass, &c., that they are employed as handles for vessels containing hot bodies, or inserted between the handles and the vessels themselves. The value of blankets depends upon the extremely low conducting power of woollen materials, and a blanket will serve equally to keep a warm body from cooling, or to keep ice from melting. The low conductivity of felt is utilised in the Norwegian cooking pot, which is a box lined with many layers of felt. The saucepan containing the food is first heated, and then placed in the box and shut in, when it will retain for a long while a temperature sufficiently high to carry on the operation of cooking.

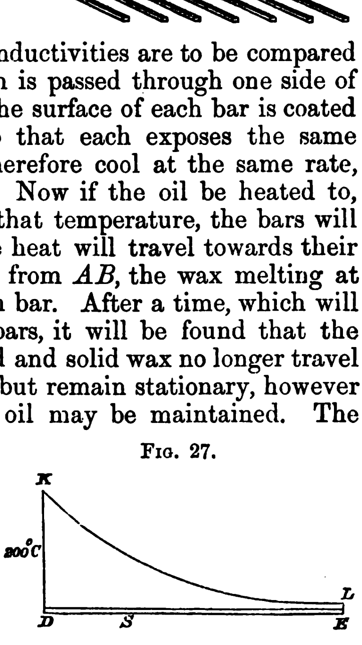
135. The *measure* of the thermal conductivity of a substance will be defined in Art. 138. The relative conductivities of different substances may be compared by means

FIG. 26.



of the arrangement shewn in fig. 26, and known as Ingenhouz's apparatus. This consists of a trough *AB* containing oil, which can be heated to a high temperature. Equal bars of the solids whose thermal conductivities are to be compared are taken, and one end of each is passed through one side of the vessel *AB* into the oil. The surface of each bar is coated with a thin layer of wax, so that each exposes the same surface to the air, and will therefore cool at the same rate, other things being the same. Now if the oil be heated to, say, 200° C., and sustained at that temperature, the bars will gradually become hot, and the heat will travel towards their extremities which are distant from *AB*, the wax melting at increasing distances along each bar. After a time, which will be different for the different bars, it will be found that the boundaries between the melted and solid wax no longer travel towards the ends of the bars, but remain stationary, however long the temperature of the oil may be maintained. The temperature of every point of the bar then remains unaltered, and if *DE*, fig. 27, represent the bar and *S* any point upon it, this will be the case when the rate of decrease of the temperature at *S* as we go towards *E* is such that the flow of heat across the section of the bar at *S* is equal to the rate at which heat is dissipated by the portion of the bar beyond *S*. The temperature of the bar will decrease in going from *D* to *E* at a rate diminishing as the distance from *D* increases. If at every point of the bar a line be drawn at right angles to its length, and proportional to the excess of the temperature of the bar at that point, above that of the air, the extremities of these lines will lie on a curve similar to *KL*. Now the wax on the bars will be melted up to the points where the temperatures of the bars are the melting point of wax, and it may be shewn

FIG. 27.

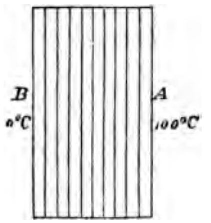


that when the wax ceases to melt any farther, if all the bars are of the same section, these distances are proportional to the thermal conductivities of the bars. Hence we have only to measure from the vessel of oil the distance on each bar along which the wax is melted in order to compare the thermal conductivities of the materials of which the bars are composed.

136. It should be borne in mind that the thermal conductivities of different bars cannot be determined by heating one end of each to the same temperature and observing the time required for points on all the bars at the same distance from the heated ends to be raised to a given temperature. For instance, in the experiment just described, we might observe the time required for the wax to be melted on each bar at a distance of three inches from the trough, after pouring the hot oil into the latter. We could not, however, in this way compare the thermal conductivities of the bars because their capacities for heat per unit of volume may be different; thus, of two bars A and B, A may have the greater conductivity, but if its capacity for heat per unit of volume be also greater than that of B, the time required to melt the wax on A may be greater than that required to melt it on B to the same distance. In order to compare the thermal conductivities, we have therefore to wait until the temperature of any point of the bars has ceased to change, or till the flow of heat becomes "steady," as explained in the next Article.

137. If one side of a plate of metal be kept in contact with water whose temperature is sustained at 100° C., while the other side is kept in contact with melting ice, heat will flow through the metal by conduction from the hot to the cold side, and after a short time the metal will acquire its permanent condition with regard to temperature under these circumstances. When this is the case, the flow of heat through the metal will be the same at all parts and continue constant so long as the temperature of its faces is kept unaltered. The flow is then said to be *steady*. *The flow of heat across the unit of area of any plate of given material is found to vary inversely as the thickness of the plate, and directly as the difference between the temperatures*

FIG. 28.



of the two faces. Now suppose the thick plate *AB*, fig. 28, to be made up of a number of thin plates of equal thickness, as in the figure. Then when the flow of heat is steady, the amount of heat which crosses each of the thin plates in a second is the same, and therefore the difference between the temperatures of the opposite faces must be the same for each plate, and the temperature of the thick plate must decrease uniformly from 100° C. on the one side to 0° C. on the other side.

If we take two plates of the same material and thickness, and suppose no heat to escape at the edges, if one side of each be kept at 100° C. and the other at 0° C., the amount of heat which will flow through each of the two plates in a given time will be obviously proportional to their areas.

138. DEF. *The number of units of heat which flow through the unit of area of a plate of unit thickness in the unit of time when the flow of heat is steady, the difference in the temperatures of the sides of the plate being 1° C., is taken as the measure of the thermal conductivity of the substance of which the plate is composed, and is called its specific thermal conductivity.*

If the unit of length be one inch, and the unit of time one second, the thermal conductivity of a substance will be measured by the number of units of heat which flow in one second across each square inch of a plate whose thickness is one inch when the temperature of one side is kept 1° C. above that of the other. If the difference of temperature be 10° C., the flow of heat will be 10 times this amount, and so on, while if the thickness of the plate be increased in any ratio, the flow will be diminished in the same ratio.

139. The thermal conductivities of some bodies have been measured by determining how much ice can be melted in a given time through a plate of known area and thickness, when one side is kept in contact with boiling water.

Suppose that a plate of wrought iron of 1 inch in thickness and 2 square feet in area is placed so as to form a division between water on the one side which is kept at 12° C. and melting ice on the other side, and suppose that at the end of an hour we find that 164 pounds of ice have been melted. The amount of heat required to melt 164 pounds of ice at 0° C. is about 12956 units :

∴ in 1 hour through 288 sq. ins. of the plate, when the temperatures of its sides differ by 12° C., 12956 units of heat flow;

∴ in 1 hour through 288 sq. ins. of the plate, when the temperatures of its sides differ by 1° C., $\frac{12956}{12}$ units of heat will flow;

∴ in 1 hour through 1 sq. in. of the plate, when the temperatures of its sides differ by 1° C., $\frac{12956}{12 \times 288}$ units of heat will flow;

∴ in 1 second through 1 sq. in. of the plate, when the temperatures of its sides differ by 1° C., $\frac{12956}{12 \times 288 \times 3600}$ units of heat will flow.

The measure of the thermal conductivity of wrought iron referred to a second and an inch as units of time and space, the unit of heat being taken, as usual, to be the amount required to raise 1 lb. of water 1° C., is therefore

$$\frac{12956}{12 \times 288 \times 3600} = \cdot 001\ldots$$

140. As another example we may find how much water at 100° C. can be evaporated per hour at atmospheric pressure in an iron boiler which exposes a surface of 20 square feet to the fire, supposing the iron to be ½ inch in thickness and the fire to keep its lower surface at a temperature of 150° C.

The thermal conductivity of iron being ·001 referred to an inch and a second, it follows that the number of units of heat passing through the iron in an hour will be

$$\cdot 001 \times 2 \times 144 \times 20 \times 3600 \times 50,$$

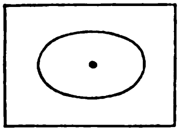
since the difference of temperature of its sides is 50° C.; and since the latent heat of steam is represented by 537, the number of pounds of water evaporated will be

$$\frac{\cdot 001 \times 2 \times 144 \times 20 \times 3600 \times 50}{537} = 1931,$$

or the quantity of water evaporated per hour will be about 193 gallons.

141. Most substances conduct heat equally well in all directions through their mass, but some crystals and organized structures conduct heat more readily in some directions than in others. Thus if a plate be cut from a quartz crystal parallel to its axis, covered with wax, and heated by a wire at the centre, the wax will be melted within an ellipse, whose major axis is parallel to the axis of the crystal, as shewn in fig. 29. This is due to the thermal conductivity of the crystal being greater in the direction of its axis than in any other direction.

FIG. 29.

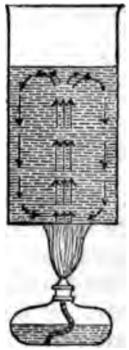


142. Pure copper and pure silver are the best conductors of heat known. Animal and vegetable substances are for the most part very bad conductors. Solids are in general very much better conductors of heat than liquids, while the thermal conductivities of gases are extremely small. Both liquids and gases are capable, however, of readily diffusing heat throughout their masses, since the extreme mobility of their parts makes up for their low conducting powers. Heat is therefore generally diffused through liquids and gases by *convection.*

143. It is a well-known fact that there is an upward current of air above and around a gas-flame, because the air which has been heated by the flame is less dense than the rest of the air in the room. For a similar reason there is a draught up a chimney when a fire is burning below it. Now suppose a gas-flame burning in the middle of a room, the doors and windows of which are closed. There will then be an upward current of hot air in the middle of the room above the flame, while a downward current must exist nearer the walls in order to supply the place of the

ascending air. In this way the air in the room will be kept in circulation, and heat will be conveyed from the gas-flame to other parts of the room *by convection.* The currents so set up are sometimes called *convection currents.*

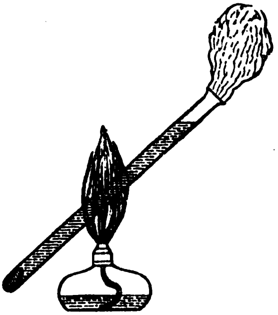
FIG. 30.



144. If a little cochineal be thrown into a vessel of water, and heat applied at the bottom, the water will be seen to circulate, an upward current being formed in the middle of the vessel immediately over the flame, while downward currents exist all round the circumference. In this way all the water is brought in turn close to the bottom of the vessel, where it is heated by conduction through the vessel itself, while the heated stream of liquid meeting, during its ascent, with colder liquid, parts with some of its heat to the latter by conduction, and thus by a combination of the processes of convection and conduction the whole of the liquid becomes heated.

It will be seen from the above that the rate at which a mass of fluid can be heated by a source of heat will depend on the position of the latter relative to it, and will generally be greatest when the heat is applied at the bottom of the liquid.

FIG. 31.



145. The very low conducting power of water may be shewn by placing a quantity of ice-cold water in a test-tube, and fixing a block of ice at the bottom. On heating the tube at about the middle point of its length, as shewn in fig. 31, the water above this point will be quickly heated by aid of convection currents, and may be made to boil before very much of the ice is melted, on account of the extreme slowness with which heat is conducted downwards to the ice, in which passage it is, after a short time, unaided by convection currents.

CHAPTER VIII.

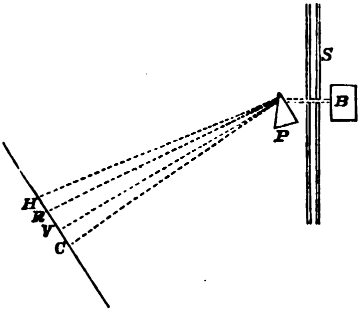
ON RADIANT ENERGY.

146. If we heat one end of a poker in the fire but not to redness, and then hold it near the face, a sensation of heat is at once felt, and we infer that some thing or some influence has passed from the poker to the face across the intervening air. If we now replace the poker in the fire and heat it to very dull redness, the same sensation is felt on bringing it to the same distance from the face, but in a stronger degree. If we now hold the poker in front of a black screen and look at the heated end through a prism, whose edge is parallel to the length of the poker, we see a dull red band slightly wider than the poker itself. If the edge of the prism be towards the left hand, the poker, when viewed through the prism, will appear more to the left than its true position. On heating it still further, till it attains a bright red heat, and again inspecting it through the prism, the red band will appear broader and brighter, and shade off into orange towards the left. On raising the temperature of the poker still more the red and orange become brighter, while yellow, green, blue, and violet bands, gradually shading into each other, are successively added towards the left. When the violet has made its appearance the poker will have attained a *white* heat, and no more tints visible to the eye will be added by further increasing the temperature, though the brightness of those already existing will be increased by this means. If the poker, at an intense white heat, be placed at a considerable distance in front of paper prepared for receiving photographic images, it will be found capable of blackening it, which *will not be* the case when the poker is red hot.

The influence proceeding from the poker which produces the sensation of heat on the skin, or of light in the eye, or which is capable of blackening photographic paper, is called the *radiation* from the poker, and the agent itself is called *radiant energy.*

147. Now let the following experiment be performed: A mass, *B* (fig. 32), of wrought iron or of platinum is heated to intense whiteness, and placed behind a double screen *S*, in which a narrow slit is cut, and a glass prism is placed in front of the screen with its edge parallel to the length of the slit. A coloured band *RV* will then appear upon a white screen placed in front of the prism, the end *R* towards the edge of the prism being red, and this is succeeded by orange, yellow, green, blue and violet towards the end *V*. If now a thermo-electric pile be moved from point to point of the coloured band, or light spectrum, the galvanometer connected with it will indicate that the face turned towards the prism is heated, and this will be the case even beyond the end *R*. If in like manner photographic paper be placed at different parts of the spectrum, it will be blackened only in the violet space, and in the space *VC* beyond the extreme violet. Let these observations be continued while the mass of metal cools. We observe, first of all, that photographic paper made to pass across the spectrum between *V* and *C* is gradually less and less blackened, till at last it is quite unaffected, while the intensity of the light spectrum gradually diminishes. The light at the extreme end of the violet then vanishes completely, and presently the whole of the violet is gone, the blue follows, then the green, and so on, while the galvanometer registers a gradual diminution in intensity in the radiation at the red end of the spectrum and in the parts beyond the red. Before all the light spectrum has vanished let the glass prism be replaced by a prism

FIG. 32.



of rock salt. The galvanometer will immediately indicate a great increase in the intensity of the radiation falling on the thermo-electric pile placed beyond the red end of the spectrum, and will also indicate the presence of rays at much greater distances beyond the red than were indicated when the glass prism was used. As the metal, *B*, continues to cool, the green, yellow, and orange lights vanish in succession, and at last, when the metal is reduced below a red heat, the last trace of red vanishes. The galvanometer, however, continues to indicate the presence of radiation beyond the red end of the spectrum, though it now gives no indication of heat when the thermo-electric pile is placed in what *was* the illuminated portion of the spectrum, shewing that when the light vanished the rays capable of heating the junctions in the thermo-electric pile vanished with it. As the mass of metal becomes cooler we have to move the thermo-electric pile still farther from the red end of the original spectrum in order to get indications of radiation, and at length the metal becomes too cold to produce any sensible effect on the pile.

This experiment may be modified, so as to be more easily performed, by substituting an electric light for the white-hot metal, and an oil-lamp for the metal when at a bright yellow heat, a piece of metal being conveniently employed for lower temperatures, but this interferes with the continuity of the results*.

In the solar spectrum the greatest intensity of the radiation, as measured by the thermo-electric pile, is a little beyond the extreme red, while the greatest amount of radiation capable of affecting photographic paper is just beyond the extreme violet end of the luminous spectrum.

148. From the experiments just described we learn that a solid body when heated below redness emits rays capable only of producing heat in bodies on which they fall, while at higher temperatures it emits rays capable of producing the

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* Instead of using a double screen as shewn in the figure it is much better to employ a thin screen and to place a lens of the same material as the prism between the latter and the slit in such a position that the slit is in its principal focus, a second lens of the same material being placed very close to the prism on the other side of such focal length that the second screen passes through its principal focus.

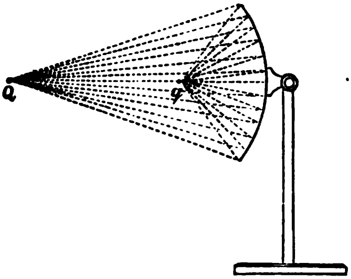
sensations of red, orange, yellow, green, blue, and violet lights, while the intensity of the heat-producing rays is increased. At still higher temperatures it also emits rays capable of producing photographic pictures, but not causing the sensation of light.

From this experiment we also infer that the *same* rays which produce the sensation of light in the eye, produce heat when allowed to fall upon other bodies, and thus we can make no distinction between light and, what has been erroneously called, radiant heat. The same is true of the radiation which produces photographic effects, though the energy of these rays is generally too feeble to produce much current in the thermo-electric pile.

149. If it be true that *some* of the rays which produce the sensation of heat are *identical* with those of light, since we cannot suppose that these rays essentially differ in kind from the other rays which produce the sensation of heat, but not that of light, we must conclude that the *whole* of the radiation which produces heat in bodies absorbing it is of the *same nature* as light, and therefore consists of vibrations of the luminiferous ether, and from the distribution of these rays over the luminous and non-luminous portions of the spectrum we are led to infer that the dark rays differ from one another and from the luminous rays in exactly the same way as the latter differ amongst themselves, that is, in wave-length, and that as the wave-lengths of the rays continue to increase as we pass along the spectrum from violet to red, so this increase continues beyond the red end. Hence bodies at a low temperature give out only those rays whose wave-lengths are very long compared with the length of a wave of light of any particular colour.

150. Again, if it be true that all the rays which are capable of producing heat are of the same nature as light, we should expect that they would be subject to the same laws of reflection and refraction. In the experiments just described we have demonstrated the refraction of the dark rays by a prism. The reflection of these rays may be shewn thus:—Take a concave mirror, *AB*, fig. 33, and place at *Q* a small source of light; then the point *q*, at which the image of *Q* is formed by the mirror, can be readily determined. Now

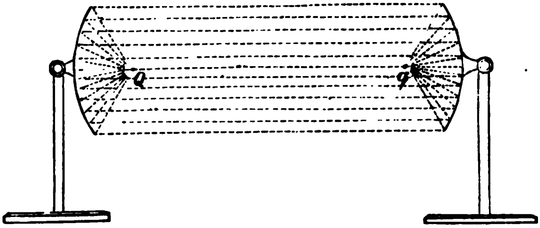
FIG. 33.



replace the luminous body at Q by a piece of metal heated just below redness, and place at q a delicate thermometer with a blackened bulb or a thermo-electric junction connected with a galvanometer. The latter will immediately indicate a high temperature; but if it be moved from q to any other point at the same distance from Q no such effect will be produced, shewing that the dark radiation from Q, which falls on the mirror, is brought to a focus at q, and that therefore these rays are subject to the same laws of reflection as those of light.

151. If two parabolic mirrors be placed opposite to one another so as to have the same axis, as in fig. 34, and the hot body be placed at Q, the focus of one mirror, while the thermometer is placed at q, the focus of the second, the distance between the mirrors may be very greatly increased without much diminishing the indication of heat by the thermometer. This follows from the fact that the rays pass from one mirror to the other, without sensibly heating the air; and, being all nearly parallel in their passage (if the body at q be small), nearly all the rays leaving the first mirror must fall on the second.

FIG. 34.



152. The preceding experiments prove that the laws of reflection for other rays are the same as those for light, *viz.* :—

(1) *The incident and reflected rays are in one plane with the normal to the reflecting surface at the point of incidence, and on opposite sides of it.*

(2) *The incident and reflected rays make equal angles with the normal to the reflecting surface at the point of incidence.*

153. In the experiment described in Art. 147, we found that on substituting a rock-salt prism for the glass prism, the galvanometer indicated an increase in the radiation falling on the pile when placed beyond the red end of the spectrum. If similar pieces of polished glass and rock salt be exposed to the same radiation, especially if the greater part of it consist of dark rays (as is usually the case), the glass will become more highly heated than the rock salt. From these two observations we infer that *glass absorbs much of the dark radiation which rock salt transmits,* the glass being thereby heated. This is equivalent to saying that rock salt is more *diathermanous* than glass, although its power of transmitting *luminous* rays, or its *transparency,* is no greater than that of glass. All bodies absorb some of the rays incident upon them, that is, are opaque (or adiathermanous) to rays of certain wave-lengths. Metals are almost perfectly opaque to all rays. (Gold in *exceedingly thin* leaves transmits green light, and silver blue light.) *All bodies absorb the same kind of rays which they themselves emit when heated.* This accounts for the dark lines in the solar spectrum, and is the basis of solar and stellar chemistry. Thus sodium vapour absorbs the yellow rays corresponding to the double D line of the solar spectrum, and emits only these luminous rays when incandescent, so that it is impossible to make sodium vapour white-hot.

154. A solution of iodine in bisulphide of carbon absorbs the *whole* of the luminous radiation from any source, while it transmits a large portion of the dark radiation. If a beam of solar light be brought to a focus in the air by a large achromatic lens and a wide vessel containing this solution be introduced in its path, the *whole* of the *light* will be cut off. (This Professor Tyndall proved by placing his eye so that the focus was formed on the retina, defending all

but the pupil by a perforated screen.) If now a small piec of platinum be placed at the point which was occupied b the luminous focus, the platinum will be heated to whit ness, shewing that the dark rays are brought to a focus a the same point as the light by the achromatic lens. (If common lens be used, the best focus of these rays is a littl beyond that of the red rays.)

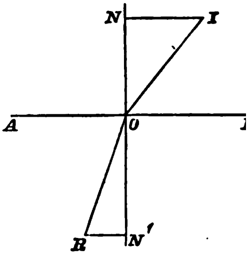
155. This experiment proves that dark radiation subject to the same laws of *refraction* as light, viz.:—

(1) *The incident and refracted rays lie in one plan with the normal to the refracting surface at the point of i cidence and on opposite sides of it.*

(2) *In passing from one given medium to another, th sine of the angle of incidence bears a constant ratio to the si of the angle of refraction, which depends only on the characte of the radiation.*

Thus, if IO represent a ray incident at O from air on a surface AB of glass and OR the refracted ray, NON' being normal to AB, ION is the angle of incidence and RON' the angle of refraction, and if we make OR equal to OI and draw IN, RN' perpendicular to NN', the ratio of IN to RN' is independent of the angle of incidence, and is called the index of refraction of the particular ray between air and glass.

FIG. 35.

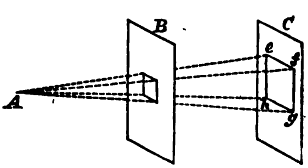


156. It is worthy of mention that when radiation pass through a considerable thickness of any particular mediu the latter absorbs all the rays which it is capable of al sorbing, and the radiation may now be made to pass throug another portion of the medium without being sensibly al sorbed by it. Thus if a beam of solar light be made to pa through a few inches of ice, it will melt the latter in t interior in the form of beautiful hexagonal flowers, like sno flakes, but may afterwards be made to pass through a lens ice without damage to the latter, and may thus be broug to a focus in which platinum may be heated to redness.

157. Many bodies absorb dark rays while they transmit luminous rays. Thus a glass fire-screen absorbs much of the non-luminous rays forming the more intense portion of the radiation from the fire; and air which contains aqueous vapour absorbs very much of the dark radiation from the earth, while it transmits the radiation of shorter wave-length from the sun. Air devoid of aqueous vapour is much more diathermanous to dark rays than air containing it.

158. Through uniform media radiation is propagated in straight lines.

FIG. 36.



Suppose radiation emitted from a very small body at A to pass through a rectangular hole in a fixed screen B, and to fall on a second screen C, which is placed parallel to B. The whole of the radiation which passes through the hole in B will fall on a rectangular area on C, and the area of this rectangle will be proportional to the square of the distance of the screen C from A. But wherever the screen C is placed, the amount of radiation which reaches it is the same, viz.:—that which passes through the hole in B. Therefore the amount of radiation which falls on each unit of area of the rectangle $efgh$ varies inversely as the area of this rectangle, that is, inversely as the square of the distance of C from A. Hence *the intensity of the radiation at any point varies inversely as the square of the distance of the point from the source.* This is known as the law of inverse squares.

159. If the direction of the screen C be changed so that it receives the radiation from A very obliquely, it will be seen that the area of C on which this radiation which passes through the hole in B falls, will be increased, and the amount of radiation falling on the unit of area will be correspondingly diminished. In this way it will be seen by the student who has read Trigonometry that *the intensity of the radiation received by* C *is proportional to the cosine of the angle of incidence.*

160. We have said (Art. 131) that heat is transmitted by radiation when it travels from one point to another *without heating the medium through which it passes.* That radiation will pass through air without sensibly heating it may be shewn by the following experiment:—Let a small piece of platinum be covered with lampblack and placed in the bulb of a differential thermometer. By means of a lens let some of the solar radiation be brought to a focus in the air within the bulb, care being taken that none of the rays fall upon the platinum. The liquid in the tube will give a very slight indication of heat (and this slight indication arises principally from the heating of the glass of the bulb and consequent heating of the air in contact with it), shewing that the air is not sensibly heated by the rays. Now let the lens be moved till the focus falls upon the platinum. The latter will be almost immediately heated to redness and will then heat the air around it, and the liquid in the tube will be rapidly driven towards the other bulb.

161. Different surfaces possess different powers of radiation; this may be shewn by constructing a metal cube, polishing one side, leaving a second with a dead metallic surface, covering a third side with velvet or other material, and a fourth with lampblack. If the cube be filled with boiling water and its sides successively presented to the thermo-electric pile at a distance of, say, one foot, the galvanometer will shew that the radiation is greatest from the side covered with lampblack, next greatest from the velvet side, and least from the polished side. This cube is called a Leslie's cube. By covering its sides with different materials we may determine their relative radiating powers.

Similarly, if two equal tin canisters be filled with hot water, and one expose to the air its polished surface, while the other is closely covered with flannel, the latter will cool more quickly than the former on account of the radiating power of the flannel. If the flannel do not *touch* the canister it will serve to keep in its heat.

From these experiments we conclude that *surfaces which reflect well radiate badly, while bad reflectors are good radiators.*

Again, if the bulb of a thermometer, or face of a thermo-electric pile, be covered with lampblack, it will absorb radiation incident upon it much more readily than if it be kept clean. A quantity of water can be boiled in a kettle whose exterior has been blackened, much more readily than in a similar kettle kept bright. Combining these results with those of the experiments just described, we infer that *surfaces which reflect well both radiate and absorb badly, while surfaces which are bad reflectors are good radiators and also absorb a large portion of the radiation incident upon them.*

We may mention that the absorbing power of any surface is generally different for the radiation from different sources. Lampblack absorbs nearly all the radiation incident upon it from any source, and for this reason the bulb of the thermometer, or face of the thermo-electric pile, employed to measure radiation, should be covered with lampblack.

THEORY OF EXCHANGES.

162. If in the focus of one of the conjugate mirrors described in Art. 151 we place the bulb of a thermometer, while a block of ice is placed in the focus of the other, the thermometer will indicate a decrease of temperature. The same would happen if the thermometer were placed in a cavity in a block of ice without touching the latter. The reason of this is that the thermometer *emits more radiation to the ice than it receives from it.* If the thermometer be placed in a room whose walls, as well as everything in the room, are at the same temperature as the thermometer, the latter will indicate no change; while if the thermometer be originally at a lower temperature than the room its temperature will increase; if, on the other hand, it be at a higher temperature than that of the room its temperature will decrease. The behaviour of the thermometer in all these cases is completely explained by Prevost's *Theory of Exchanges.*

This theory asserts that every body radiates at a rate depending only on the nature and temperature of its surface, while it absorbs a certain fraction of the radiation it receives from other bodies, which fraction is a measure of the absorbing power of its surface.

163. From the fact that a surface appears equally bright in whatever direction it be viewed it follows that

The amount of radiation emitted by any surface is greatest in the direction of the normal to the surface, and that for other directions the amount is proportional to the cosine of the angle which the direction makes with the normal. Also we have seen (Art. 158) that

The intensity of radiation at any point varies inversely as the square of its distance from the source.

From these data it may be shewn geometrically that if two bodies, *A* and *B*, which emit the same amount of radiation per unit of area of their surfaces, be placed near to each other, the amount of radiation reaching *A* from *B* is equal to the amount from *A* which falls on *B*.

Suppose a thermometer to be placed with its bulb at the centre of a hollow sphere, which is initially at the same temperature as the thermometer, and any part of whose surface is capable of radiating ten times as much as an equal portion of the surface of the thermometer bulb at the same temperature. Experiment shews that the thermometer always retains the temperature of the enclosure in which it is placed. Suppose also that the surface of the sphere absorbs one-half of the radiation which falls upon it from the thermometer, the other half being returned to the thermometer by reflection. Then if the surface of the sphere radiated as much per unit of its area as that of the thermometer, just as much radiation would reach the thermometer from the sphere as the thermometer itself gives out; for, while the whole of the latter reaches the sphere, only a very small part of the radiation from the parts of the sphere reaches the small bulb at its centre, viz. that part of the radiation which leaves the surface of the sphere along the radius, or nearly in that direction. But since the sphere radiates ten times as much per unit of area as does the thermometer bulb, it follows that ten times as much radiation reaches the thermometer from the sphere as reaches the sphere from the thermometer; and since the thermometer retains the same temperature, and no heat can be lost by it except by entering the sphere, it follows that in each second *the thermometer* *must absorb the same amount of heat from the sphere as the sphere absorbs from the thermometer.* But the sphere absorbs half of the total radiation from the thermometer. Therefore the thermometer must absorb one-twentieth of the radiation which reaches it from the sphere. Hence while the spherical surface absorbs one-half of the total radiation from the thermometer, the latter absorbs but one-twentieth of that which it receives from the sphere, or the absorbing powers of the two surfaces are directly proportional to their radiating powers. Now whatever be the nature of the surfaces of the sphere and thermometer, the latter will always retain the temperature of the former; hence we conclude that if we measure the absorbing power of a surface by the ratio of the amount of radiation it absorbs to the whole amount incident upon it,

The absorbing power of any surface, A, *for radiation emitted from any other surface,* B, *is to the absorbing power of* B *for radiation reaching it from* A, *as the radiating power of* A *is to that of* B.

164. As we have stated above, it may be shewn by geometry that if two bodies *A* and *B*, which emit the same amount of radiation per unit of area of their surfaces, be placed near each other, the amount of radiation from *B* which falls on *A* is equal to the amount from *A* which reaches *B*. Hence if any number of bodies, all at the same temperature, be placed in the neighbourhood of one another, each will emit radiation to, and receive radiation from, all the others, and the amount of radiation from any body *B* which any other body *A* absorbs, is exactly equal to the amount of radiation from *A* absorbed by *B*.

Now suppose that two bodies *A* and *B* are near to each other, and the temperature of *B* is higher than that of *A*; also suppose that the surface of *B* has ten times the radiating power possessed by *A*, and therefore ten times the absorbing power; and moreover that *B* absorbs half the radiation falling upon it from *A*. Then, by what we have proved, *A* will absorb one-twentieth of the radiation reaching it from *B*. But since *B* is at a higher temperature than *A*, *more than* ten times as múch radiation reaches *A* from *B* (of which *A* absorbs one-twentieth) as reaches *B* from *A* (of which *B* absorbs one-half). Hence *A* absorbs more radiation from *B* than *B* absorbs from *A*, and thus the temperature of *A* will be raised while that of *B* will fall. Thus if *A* be a block of ice, and *B* a thermometer originally at 15° C., and everything else in the room including the walls be at 15° C., the temperature of the thermometer will fall on account of the presence of the ice, while if the ice be removed the thermometer is capable of receiving radiation from the wall, in the directions previously subtended by the ice, and thus its temperature will be again raised to 15° C. and kept there.

The following is a brief summary of our results.

165. Prevost's Theory of Exchanges may be thus stated:

Every body emits radiation in all directions at a rate depending only on its temperature and the nature of its surface, while it absorbs radiation from all bodies to which it is exposed.

Combining this with the known fact that a body placed in an enclosure kept at constant temperature acquires the temperature of the enclosure, we see that the following law must be true, viz.:—

The absorbing power of any surface, A, *for radiation emitted from any other surface,* B, *is to the absorbing power of* B *for the radiation from* A *as the radiating power of* A *is to that of* B*; the absorbing power of a surface being measured by the ratio of the radiation it absorbs to the whole radiation incident upon it.*

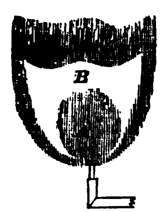
166. When radiation falls upon a transparent, or diathermanous, body, as rock salt, or air, part of the radiation is absorbed within the body, and the absorption goes on as the radiation traverses it until all those particular rays which it is capable of absorbing have been filtered out, and the remaining radiation is then transmitted by the body without sensible diminution. On examining the spectrum of radiation after traversing such a medium it will be found to be crossed by a number of absorption bands the radiation corresponding to which has been removed, leaving black spaces in

the luminous portion of the spectrum, spaces in which a thermo-electric junction is unaffected in the parts beyond the red, and spaces in which photographic paper is unblackened beyond the violet. If the body be heated so as to become self-luminous it will be found that it emits those rays which in the previous case it has absorbed.

167. Flame consists of gases heated so as to become self-luminous. Now gases (as we have seen in the case of air in Art. 160) possess very little power of absorbing radiation, and consequently possess very little power of emitting it. Hence a flame which contains within it no solid particles generally emits very little light. The flame of hydrogen burning in air or pure oxygen is scarcely visible in ordinary daylight, but if a piece of lime be heated by it we obtain the oxy-hydrogen lime light. When the pressure under which gases are burning is very much increased, so that their density is increased, they give out much more light than under ordinary circumstances.

168. The radiation from an ordinary gas or candle flame is due principally to the presence of solid particles of carbon within it, and the illuminating power of coal gas depends on the amount of carbon it contains. An ordinary candle, or coal-gas, flame consists of three distinct portions. The central portion, *A*, fig. 37, called the area of non-combustion, contains gas which has not yet met with air, and is therefore not burning, and being at a comparatively low temperature is non-luminous. Surrounding this area is another in which the gas has met with a partial but insufficient supply of oxygen, and in it a portion of the gas is burned while solid particles of carbon formed by its decomposition are raised to a very intense heat and emit much radiation. This is called the area of partial combustion and is marked *B* in the figure. Beyond this is the area of complete combustion, *C*, in which the particles of carbon are burned up, and since this area consists only of heated gas it emits very little radiation, although it is the hottest part of the flame.

FIG. 37.



7—2

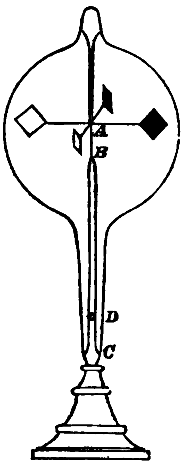
If the gas be mixed with air before being ignited, as in the flame of a Bunsen or gauze burner, the solid particles of carbon do not exist in it for a sensible time, and very little radiation is emitted. If the hand be held by the side of a Bunsen flame and the supply of air be suddenly cut off so as to make the flame bright, the sensation of heat experienced by the hand will be at once very sensibly increased.

169. In 1874 Mr Crookes discovered that when radiation was received by a body in an almost perfect vacuum it had a tendency to move in a direction opposite to that from which the radiation came, that is, to recede from the source of radiation. In his first experiments a small light body, such as a piece of elder pith, was attached to each end of a straw through the middle of which half a needle, pointed at both ends, was passed, and the straw was supported in a horizontal tube upon the points of the half needle, which was a little shorter than the diameter of the tube. The balance was effected by heating the heavier end so as to dry it. When the tube was exhausted by a mercurial air-pump it was at first found that a hot body appeared to attract the end of the straw near to which it was placed, but when the exhaustion reached a certain stage, which was different for different bodies balanced on the straw, the attraction ceased and repulsion set in. This repulsion was not due to currents of air, because it took place equally whether the hot body was placed below or *above* the straw. On substituting a piece of ice for the hot body the ice appeared to attract the end of the straw near to which it was placed.

Mr Crookes thus found that if pieces of metal were balanced on the straw the repulsion was greater when they were covered with lampblack than when polished, and that generally the repulsion was greater the greater the absorbing power of the surface. From this it would follow that if a disc of metal were polished on one side and covered with lampblack on the other and were exposed to radiation equally from all directions (as in diffused daylight) it would tend to move in the direction of the normal to its surface *drawn outwards* from its polished side, that is, the polished side would always appear to advance and the black side to retire. Upon this principle Mr Crookes constructed the *Radiometer*, a modification of which is shewn in fig. 38.

It consists of a glass vessel into the bottom of which is sealed a tube, which is drawn off at the top and carries a sharp steel point. On this rests a light glass cup, *A*, which carries four vertical discs of aluminium at the extremities of horizontal arms at right angles to each other. The discs are thus supported on a bearing similar to that of an ordinary compass needle. A very narrow glass tube attached to the top of the vessel prevents the cup from falling off the point if the instrument be inverted. The vessel is exhausted through the tube *BC*, in which a hole *D* has been formed for this purpose, and the end of the tube is then sealed. The discs are covered with lampblack on one side only, and are arranged in order, so that the black sides all point in the same direction round a horizontal circle. From what has been said it will be seen that, with this arrangement, the arms carrying the discs will rotate when the latter are exposed to radiation, in the direction in which the polished faces look, in the same way as the arms of an anemometer carrying Robinson's cups rotate in the direction in which the *convex* surfaces of the cups look. The rate at which the arms revolve may be taken to indicate the intensity of the radiation to which the instrument is exposed, and hence its name.

Fig. 38.



It appears at first sight as if the action of the radiometer might be due to the impact of material particles, and thus seem to favour the corpuscular theory of radiation; but were the corpuscular theory true, the pressure on the polished surfaces at which reflection takes place, and from which the particles must therefore rebound, would be greater than that upon the blackened surfaces, which must retain them, and the arms would revolve in the direction opposite to that in which they actually move.

Perhaps the best explanation hitherto given of the repulsion produced by radiation is that due to Professor Tait, of which the following is a brief sketch.

Although a very good vacuum may have been produced within the receiver, there are always present some particles of air, or other gas, which, according to the dynamical theory of gases, are moving about in all directions, with velocities which increase with the temperature, and which exert pressure upon any surface exposed to their impacts. Now the surface of any body exposed to radiation becomes heated thereby, and the more so as its absorbing power is increased. Hence in the radiometer the blackened sides of the vanes become heated more than the polished sides. When the particles of air strike the surface, they rebound with velocities which on the average are greater than those with which they strike it if the temperature of the surface be higher than that of the enclosure, and thus act like elastic balls whose coefficient of elasticity is greater than unity. The greater the velocity with which they rebound, the greater is the pressure they exert on the surface, and this pressure will therefore be greater the higher the temperature of the surface. The pressure of the air on the side of a body exposed to a source of radiation will therefore be greater than that on the opposite side, and the body will consequently appear to be repelled by the source; while in the radiometer the pressure of the air on the blackened faces will be greater than that on the polished faces, because their temperature is higher, and the arms will therefore rotate in the direction in which they are observed to move.

CHAPTER IX.

METEOROLOGY.

170. We have now to consider the application of some of the experimental results we have obtained to the explanation of natural phenomena. We have seen that if air be heated without increasing the pressure to which it is exposed it expands considerably. Hence hot air will rise in cold air on account of the action of gravity. Now during a hot day the sun heats the surface of the land and of the sea, but owing to cooling by the evaporation of the latter, and communication of heat to the water below on account of the continual movements of the sea, while the land is for the most part a very bad conductor of heat, the surface of the sea, and consequently the air in contact with it, becomes much less heated than that of the land. The air above the land being therefore more highly heated than that over the sea will ascend, and air from the sea will flow in to occupy its place, forming a *sea breeze.*

During the night the land parts with its heat by radiation and becomes much more cooled than the sea, on account of the low radiating power and high specific heat of the latter. The wind then blows from the land to the sea, since the air above the sea ascends, thus forming during the night a *land breeze.*

171. The equatorial regions of the earth become highly heated by the sun, which is vertical, or nearly so, in these regions at noon. The air there becomes consequently less dense than that in the adjoining temperate zones, and therefore ascends to give place to the colder air, which, under the action of gravity, flows in from North and South, thus

tending to produce a North wind on the borders of the temperate and tropical zones in the Northern Hemisphere, and a South wind in the corresponding regions of the Southern Hemisphere. Now the surface of the earth near the equator has a velocity from West to East of more than a thousand miles an hour, on account of the earth's rotation, while places in higher latitudes have a less velocity. As the air, then, flows towards the equatorial regions it is continually reaching places which have a greater velocity from West to East than those from which it comes, and, since it cannot immediately acquire this velocity, it has always a motion from *East to West* relative to the place over which it passes. Combining this with its previous motion towards the equator we get a North East wind in the Northern Hemisphere and a South East wind in the Southern Hemisphere. These are the *trade winds.*

172. Now the air which ascended at the equator must come down somewhere to take the place of the air which flowed towards the equator from higher latitudes and make room for the air which continues to rise at and near the equator. This current of air on reaching the earth's surface has, of course, a motion towards the nearer pole, but since it comes from places whose motion, on account of the rotation of the earth, is greater than those to which it is travelling, it will always have a velocity relative to these latter places in the direction in which the earth is turning, that is, from *West to East,* and combining this motion with its motion towards the pole we get a South West wind in the Northern Hemisphere and a North West wind in the Southern Hemisphere. These are the *Counter Trades.*

173. On account of the great amount of heat absorbed by water in evaporating, the presence of a large quantity of water will have a great effect in moderating the excessive heat of the climate in summer, and its high specific heat enables it to give out so much heat while being cooled in winter as to considerably alleviate the cold in that season. The great equatorial current which (probably partly driven by the trade winds) has a motion from east to west in the Atlantic Ocean, and rushing into the Gulf of Mexico,

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sion, all to exist as vapour, and a portion of it con-
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at the resistance offered to their motion by the air
ient to prevent their falling through it except with
cedingly small velocity. The cloud seen to form in
of the spout of a tea-kettle containing boiling water, or
the safety valve of a steam boiler, consists of small
s of water, and not of steam, which is invisible. In the
of a kettle in which the water boils violently the steam
nvisible for some distance in front of the spout.

175. Cloud may also be formed by a warm wind blowing against the side of a cold mountain. Here the wind is cooled by actual contact with the mountain, as well as by having to ascend its sides and so expanding under diminished pressure. As the air leaves the mountain the cloud sometimes evaporates, so that there *appears* to be a stationary cloud around the mountain top notwithstanding the presence of a strong wind. The cloud is, however, continually being blown away and renewed.

From this we should expect mountains to exert a great influence on the condensation taking place in their neighbourhood, and it is a matter of observation that the rainfall in mountainous districts is, other things being the same, much greater than on extensive plains.

176. Another cause of condensation is the mingling of currents of air at different temperatures. The pressure which aqueous vapour can exert at the mean of two temperatures is considerably less than the mean of the pressures it can exert at those separate temperatures, and consequently when two quantities of air at different temperatures mix, if each be originally saturated with aqueous vapour a portion of this must be condensed.

Thus the greatest pressure of aqueous vapour at 5° C. is about ·257 in. of mercury, while at 15° C. it is about ·5 in. The mean of these is ·3785 in., but the greatest pressure of aqueous vapour at 10° C. is only ·36 in. Now suppose two equal masses of air, saturated with aqueous vapour at the temperatures of 5° C. and 15° C. respectively, to mix. The temperature of the mass would then be reduced nearly to 10° C., and consequently a portion of the vapour will be condensed till its pressure is only ·36 in., instead of ·3785 in., or about 5 per cent. of the whole amount of vapour in the two masses of air will be precipitated to form cloud. During this condensation the vapour which is condensed gives up to the air the latent heat of evaporation, thus preventing it from being cooled quite to the mean of the two temperatures, and also diminishing accordingly the amount of precipitation.

In all these cases *cloud is formed by the cooling of the air below the* DEW-POINT.

When a cloud is formed near the surface of the earth, it forms a *fog* or *mist*.

177. When some of the small drops of water in a cloud unite to form larger drops, they fall more rapidly than the others, and meeting with the small drops as they fall through the cloud, they attach themselves to them, thus increasing *their own* bulk and in consequence falling more rapidly.

The union of the small drops or *vesicles* of water of a cloud or fog thus produces *rain*.

The very great amount of evaporation taking place in the equatorial regions, and the strong upward current of air there produced, account for the enormous rainfall in those parts.

178. If, as the small raindrops fall, they pass through colder regions of the atmosphere, they become frozen, and thus fall as *hail*.

If a cloud exist at a temperature below 0° C., or be formed by the mingling of a quantity of warm air with air so cold that the temperature of the mixture is below 0° C., the condensed vapour will consist of minute crystals of ice. It is these small ice crystals which form *halos* round the moon on cold nights, and sometimes, especially in the early morning, produce beautiful halos round the sun. The union of these small crystals produces *snow* flakes, which grow as they descend by the aggregation of other crystals to their exterior.

We have stated (Art. 110) that water may under special circumstances be cooled below 0° C. without freezing. Now and then this happens to raindrops which fall as water, but as soon as they meet with any disturbing body they congeal, forming a solid sheet of ice over the surface of an umbrella, or any other body on which they may fall, although its temperature may have been initially above 0°C.

179. The earth in any locality emits radiation at a rate depending upon the nature and temperature of its surface. During the day it receives radiation from the sun, but during the night this is not the case, and a loss of temperature is the result. If the night be cloudy, the clouds radiate to the earth almost as much heat as they receive from it, so that its temperature is not much reduced; but if the night be clear, the surface of the earth radiates into space, and receiving nothing in return, a cold night is the result. The air very close to the earth, then, frequently becomes cooled below the dew-point, especially if the day has been warm, and a white mist is seen to cover the land, particularly where grass, or the like, is growing. This

mist deposited on the surface of the earth, of plants, &c., is *dew*.

Very much more dew is deposited on grass and similar vegetable structures than upon the bare earth, or stones. The reason of this is that the blades of grass are exceedingly good radiators, but very bad conductors of heat; they therefore become intensely cold, and the air around them being cooled by contact, deposits very much of its moisture upon their surfaces. Stones and the like are not such good radiators as blades of grass, while their conductivity is much greater, so that they receive heat by conduction from the ground below, to make up in part for that which they lose by radiation.

On account of the great radiating power but small conductivity of straw, the water in shallow vessels, if exposed upon a heap of straw, may be frozen during the night in hot regions of India.

180. When the temperature of the surface of the ground, or of other surfaces, is reduced by radiation below 0° C., this temperature being also below the dew-point of the surrounding air, the aqueous vapour becomes frozen as it is condensed, and thus *hoar-frost* is produced.

The theory of Dew was first clearly worked out by William Charles Wells, a London physician, and the student interested in the subject is recommended to consult his essay, edited by Mr L. P. Casella, and published by Messrs Longman and Co. in 1866.

CHAPTER X.

ON THE RELATIONS BETWEEN HEAT AND WORK.

181. IN the introductory chapter of this work we shewed how mechanical motion is sometimes converted into heat, and we were thus enabled to trace the energy of a moving system which in Newton's time was supposed to be destroyed by friction.

It was formerly believed that heat consisted of a kind of imponderable fluid which pervaded all bodies, and that when heat was produced by the blow of a hammer, or the sudden compression of air, it was *squeezed out* of the body operated upon, by the pressure to which it was exposed.

For some centuries past there have however generally been philosophers who could not accept this doctrine but who believed that heat consists of a "brisk agitation," or vibration, of the minute particles of which material bodies are composed. This theory, however, does not appear to have been very generally accepted until the present century, and Sir Benjamin Thompson, Count of Rumford, an English Engineer of American birth, employed in the manufacture of artillery by the Bavarian Government, was perhaps the first to establish it upon a sound scientific basis.

182. Count Rumford observed that during the boring of cannon a large amount of heat was evolved, far more than he could suppose to be squeezed out of the borings which were removed by the cutters. In order further to investigate this point he caused a blunt steel borer to press against the interior of a brass cylindrical cup which was placed in a wooden box containing 18·77 pounds of water, initially at a tempera-

ture of 15·5° C., and two horses were employed in making the brass cylinder rotate, the steel bar being kept stationary. In 2½ hours the 18·77 pounds of water boiled. Rumford measured the capacity for heat of the borings removed from the cylinder, and shewed it was not different from that of an equal mass of unbroken metal, so that the heat could not possibly have been derived from these. In a paper read by him in 1798 before the Royal Society, after describing this experiment, he adds:

"It appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated, in the manner the heat was excited and communicated in these experiments, except it be MOTION."

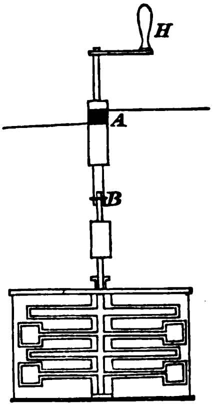
Shortly after Rumford's experiments Sir Humphry Davy found that friction between two blocks of ice was capable of melting them when they were vigorously rubbed together, and from this experiment he arrived at the same conclusion as Rumford.

183. After Rumford's experiments not much more was done in the subject until Dr Mayer, about the year 1842, endeavoured to determine "*the mechanical equivalent of heat,*" that is, *the amount of work, which, if entirely converted into heat, will produce sufficient to raise the temperature of one pound of water* 1° *C.* Mayer's experiments were carried out upon air, but, though he arrived at a very accurate result, his reasoning was not sound because he did not leave the air in the same state as he found it. The missing link in Mayer's experiments was however supplied by Dr Joule when he shewed that the temperature of a mass of air was unaffected by its expansion into a vacuum.

184. To Dr Joule, of Manchester, belongs the credit of having first determined the mechanical equivalent of heat with great accuracy by a course of investigation which was logically complete. His best experiments were carried out in 1849, and consisted in determining the amount of heat generated by the friction of a metal paddle in vessels containing water and mercury, and also by the friction of bevel wheels of cast iron against each other, the amount of work

expended in driving the apparatus being measured. The arrangement employed to produce friction in water consisted of eight paddles made to revolve in a cylindrical box of water between stationary vanes, as in an ordinary churn. The forms of the paddles and vanes are shewn in fig. 39. The paddles were made to revolve by a weight which in its descent turned a roller, around which part of a string was wound, another part of the same string being wound round the cylinder *A*, which could be coupled, by a pin *B*, to the paddle. When the weight had run down it was wound up by turning the handle *H* after removing the pin *B*, when, the coupling being removed, the paddle was unaffected by the motion of the handle. The mass of the driving weight being known, as well as the whole distance through which it fell, the whole amount of work done upon the apparatus was determined in foot-pounds, and allowance made for all resistances outside the box containing the water. The temperature of the water in the vessel was observed during the experiment, and thermometers by which a variation in temperature of $\frac{1}{400}$°C. could be detected were employed; the amount of water as well as the capacity for heat of the vessel and paddle were carefully measured and allowance made for conduction. These experimental data are all that are required for the determination of the mechanical equivalent of heat, and Joule's results shewed that *the amount of work which must be entirely converted into heat, in order to raise the temperature of one pound of water* 1° *C. from* 0° *C., is* 1390 *foot-pounds.* Hence, according to Joule,

FIG. 39.



If for the unit of heat be taken the amount required to raise the temperature of 1 *lb. of water* 1° *C. from* 0° *C., the mechanical equivalent of heat is* 1390 *foot-pounds.*

185. For example, the amount of heat which would be produced by the fall of 100 tons of stone through a vertical height of 1000 feet down the side of a mountain, supposing the

mass to come to rest at the end of this distance, would raise the temperature of $\frac{2240 \times 100 \times 1000}{1390}$ pounds, $= 161{,}151$ pounds, of ice-cold water 1° C., or would convert about 313 lbs. of water initially at 0° C. into steam at 100° C.

(In this case, as explained in our introductory chapter, the potential energy initially possessed by the earth and stone on account of their relative positions is converted into kinetic energy in the fall and this into heat, or thermic energy, by striking the ground.)

186. We have seen that work may be readily converted entirely into heat. Heat must therefore be of the same nature as work, that is, a form of energy, and by means of its mechanical equivalent quantities of heat and of other forms of energy become comparable.

As work can be converted into heat, so, by proper appliances, heat may be converted into work. An appliance for this purpose is called a *heat engine*. Steam engines, hot air engines, gas engines and the like, are forms of heat engines. The conversion of heat into work may be shewn by taking a quantity of air compressed in a tall cylinder by a number of weights placed upon a piston which fits it. By removing the weights one by one the air will expand, and in doing so will lift the weights left on the piston, and therefore do work. If the weights be removed in sufficiently quick succession the air will be found to be cooled by its expansion. Now Joule shewed that when air expanded into vacuum, and consequently did no external work during its expansion, its temperature was on the whole unaffected. Hence the loss of temperature of the air lifting the weight must be due to a conversion of part of its heat into work*. Again, it is found that more heat is required to raise the temperature of a mass of air through a given number of degrees when it is allowed to expand against a constant pressure than when its volume is kept constant, in other words, the specific heat of air at constant pressure is greater than its specific heat at constant volume. But its temperature is unaffected by change of volume when it does no external work though no heat is allowed to enter or leave it. Hence the difference between the two specific heats must be due to the heat converted into external work when the gas is allowed to expand.

---

* The molecular theory of gases completely explains this result, because, when the piston is rising it is moving in the direction in which the particles of gas strike it; they therefore rebound with diminished velocity, and although they behave like *perfectly* elastic balls, they lose energy, that is, *they lose heat*, by the impact.

187. From what we have said, it will appear that the mechanical equivalent of heat enables us, if we know the specific heat of air at constant pressure, to determine its specific heat at constant volume. The method will be made clear by the following example.

Suppose a cubic foot of air under a pressure of 15 lbs. weight per square inch and at 10° C. to weigh $1\frac{1}{4}$ ozs., and suppose its specific heat at constant pressure to be ·237. Let the air be placed in a cylinder closed by a piston whose area is one square foot, the weight of the piston being so counterpoised that the pressure on the air in the cylinder is equal to the weight of 15 lbs. on each square inch. Then the whole pressure of the air on the piston will be equal to the weight of 144 × 15 lbs., that is, of 2160 lbs. Now let the air be heated to 100° C. It will then expand (Art. 79) till its volume is $\frac{373}{283}$ cubic feet, and will therefore raise the piston through $\frac{90}{283}$ feet. Hence the work done by the air in expanding will be $\frac{2160 \times 90}{283}$ foot-pounds, or about 687 foot-pounds. The mechanical equivalent of heat being 1390 foot-pounds, the amount of heat consumed in doing this work would raise the temperature of $\frac{2160 \times 90}{283 \times 1390}$ pounds of water 1° C.

Now the mass of air heated is $1\frac{1}{4}$ ozs. or $\frac{5}{64}$ of a pound, and its temperature is raised through 90° C., its specific heat being ·237. The amount of heat employed would therefore raise through 1° C. the temperature of $\frac{5 \times 90 \times \cdot 237}{64}$ lbs. of water, or of 1·666 lbs. of water. But of this number of units of heat $\frac{2160 \times 90}{283 \times 1390}$, or ·4942, units is consumed in doing external work. Therefore the amount employed in actually raising the temperature of $\frac{5}{64}$ lbs. of air through 90° C. is 1·6666 − ·4942, or 1·1724 units. But since air is not cooled by expansion if it do no external work, this amount is the same as would be required to raise the temperature of the same air to the same extent, if its volume were kept constant. Hence to raise the temperature of $\frac{5}{64}$ lbs. of air through 90°C. at constant volume we require 1·1724 units of heat, and the specific heat of air at constant volume is therefore

$$\frac{1{\cdot}1724 \times 64}{90 \times 5} = {\cdot}1667\ldots$$

From this we see that the ratio of the specific heat of air at constant pressure to its specific heat at constant volume is $\frac{{\cdot}237\ldots}{{\cdot}166\ldots} = 1{\cdot}42\ldots$ According to the best experiments the value of this ratio for air and other permanent gases is between 1·41 and 1·42.

188. We have said that heat engines are capable of converting heat into work, and this is usually effected by taking advantage of the expansion of some substance when heated. This substance is called the *working substance.* If the engine, after a complete stroke, leaves the working substance in the same state in which it finds it, so that it is capable of employing the same substance an indefinite number of times in succession, the substance is said to go through a complete *cycle* of changes; as, for instance, when the waste steam from an engine is condensed and returned to the boiler.

189. An engine can convert heat into work only by allowing heat to pass into the working substance from a *source* at a high temperature, and allowing *part* of this to escape from the substance to a *condenser* at a lower temperature. Thus the engine cannot convert the whole *of the heat it* receives from the source into work.

The ratio of the amount of heat which an engine converts into work to the amount received from the source is called the EFFICIENCY *of the engine.*

In measuring the efficiency of an engine the working substance is supposed to be left by the engine in the *same condition as to temperature and volume* as that in which it was found by it. Otherwise the engine might utilize some of the energy *contained in the substance itself,* and so leave it deprived of part of its energy, as when air does work in expanding under a continually diminishing pressure without receiving any heat from without.

190. If two bodies at different temperatures be placed in contact, heat will pass from the hot to the cold body without doing any work on the way. We might thus allow the whole of the heat from the source to pass into the condenser without doing any work. In order then to make the most of the heat supplied by the source, we must so arrange matters that when heat passes from the source into the working substance, or from the working substance to the condenser, the difference of temperature in each case is the least possible. The *efficiency* of the engine will then be a maximum.

191. It can be shewn that if this difference of temperature could be made indefinitely small, and no heat be allowed to leave the working substance by radiation or conduction, except that which enters the condenser, the efficiency of the engine would be very nearly proportional to the difference between the temperatures of the source and condenser divided by the temperature of the source, reckoned from the absolute zero of the air thermometer. A scale of temperature for which this proportionality is exact instead of approximate is known as Thomson's Absolute scale of temperature, having been first proposed by Sir William Thomson. The difference between it and the scale of the air thermometer described in Art. 80 is almost insensible. This scale is independent of the properties of any particular substance, and is therefore entitled to be called the *absolute* scale of temperature.

192. *Suppose an engine which satisfies the above conditions to be supplied by heat from a source at* 250° *C. and to give out heat to a condenser at* 100° *C. Suppose also that the engine works at the rate of* 10 *horse-power; it is required to find the amount of heat taken from the source and the amount given out to the condenser per hour.*

The measure of the efficiency of the engine is $\frac{250-100}{250+273}$ or $\frac{150}{523}$. Now the work done per hour is $33000 \times 10 \times 60$ foot-pounds = 19,800,000 foot-pounds, and this implies the conversion into work of $\frac{19800000}{1390}$, or 14244·6..., units of heat. But only $\frac{150}{523}$ of the heat received is converted into work, while the remaining $\frac{373}{523}$ of the heat is given out to the condenser. Hence the number of units of heat received per hour from the source is $14244{\cdot}6 \times \frac{523}{150} = 49666{\cdot}1\ldots$, and the amount given out to the condenser is this quantity less that converted into work, viz. about 35421·5... units.

193. From what we have said it will appear that our ability to convert heat into work depends on our power of commanding differences of temperature, and the *availability* of any quantity of heat for useful purposes depends upon the difference between the temperature of the body containing it and the lowest temperature we can command. Now if we have a hot and cold body and a heat engine, part of the heat of the hot body can be converted into, or is available for, work; but if the bodies be placed in contact they will eventually attain the same temperature, and though no heat has been lost by the two together, yet that which they contain is no longer available for conversion into work without the introduction of a colder body. If we could obtain no differences of temperature heat engines would have no existence. Thus although the whole amount of *energy* possessed by a system of bodies unacted upon by

anything from without remains unaltered, yet the *availability* for doing external work of this energy is continually diminishing. The principle involved in this statement is called the principle of the *Dissipation of Energy.*

194. Our first chapter was concerned with the Principle of Conservation of Energy which teaches us that, though Energy may be transformed, it cannot be created or destroyed except by the direct action of a Supernatural Agent, and we must now conclude with this brief glance at the Principle of Dissipation of Energy which states that, though energy cannot be destroyed or created by natural agents, yet there is a tendency in nature for such transformations as diminish the available energy of any material system to continually occur. It is impossible in a work like this to give any satisfactory account of the theory of heat engines, or of Sir William Thomson's absolute scale of temperature, and we strongly recommend the reader not to be satisfied with the very imperfect sketch here given, but to consult Professor J. Clerk Maxwell's *Theory of Heat,* in which a very perfect outline of our present knowledge on this subject will be found.

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CONTENTS.

CLASSICAL

Page
Bibliotheca Classica 67
Grammar-School Classics 68
Cambridge Greek and Latin Texts 69
Cambridge Texts with Notes 70
Public School Series 71
Critical and Annotated Editions 72
Latin and Greek Class Books 74
Classical Tables 76
Translations, &c., adapted for School Prizes . . 76

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Cambridge School and College Text Books . . 79
Arithmetic and Algebra 80
Geometry and Euclid 81
Trigonometry 82
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